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Civil Defense Shelters
A State-of-the-Art Assessment—1986

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EXECUTIVE SUMMARY

This report is a comprehensive review of what is known about shelters from the available literature in the United States. An attempt has been made to concentrate on the information which should be known by a U.S. planner. Shelter against a number of natural and technological hazards is considered, but the most important threat, and the one about which the most information exists, is shelter against nuclear weapons effects.

The most important fact to recognize is that there is a very well developed technology for the protection of civilians against the effects of nuclear weapons. It is potentially very effective and has been extensively tested against real nuclear weapons in the 1950s and, subsequently, blast tested with large high-explosive charges and shock simulation techniques. Design techniques are covered in a variety of manuals, and all such techniques will produce shelters that will be very highly effective. In the past, the reliability of design was often attained at the cost of great conservatism and excessive expense. The present state of the art in structural design of blast shelters is comprehensively described in the 1985 update of the American Society of Civil Engineers' Manual No. 42, Design of Structures to Resist Nuclear Weapon Effects.

The threat to the American public from nuclear weapons is now believed to be of such magnitude that a full shelter program would have to include 160 million blast-shelter spaces and approximately 80 million fallout-shelter spaces. Blast protection is believed to be required in the areas surrounding military targets and urban-industrial areas. Fallout protection is believed to be required over the entire country.

Existing structures, particularly large masonry or concrete buildings, can provide significant, though varying, amounts of fallout protection. An effort by the U.S. Government to identify such structures in the 1960s and 1970s, has identified an inventory of 245 million spaces which can provide protection factors of 40 or more against fallout radiation. Unfortunately, most of these spaces are in what are presently believed to be risk areas, and many of them are in the upper stories of multistory buildings, which are vulnerable to blast effects. The basements of concrete buildings provide some protection against blast effects but only at low overpressures. There is not nearly enough of this "best available" space to protect more than a very small fraction of the risk area population. With today's resources, the only hope of survival of the risk area population in an all-out attack would be a large-scale evacuation of the target areas during the days preceding the attack.

If several hours' or days' warning of an attack are available, highly effective fallout shelter can be improvised. This protection can include improvisation of shelter in a basement by stacking books, furniture, bags and boxes of earth, and other mass on and around a table in a protected corner.

In the 1970s, a technology for producing effective shelter from tools, materials, and labor at hand was developed. This technique called "expedient shelter" involved the construction of covered foxholes or covered trenches. All these shelters provide fallout protection factors in excess of 100. In the Defense Nuclear Agency's 600-ton, high-explosive field tests, the designs using unshored trenches survived blast overpressures in the region of 5 to 7 psi. Lightly-shored versions survived 15 or more psi and one design has repeatedly survived overpressures in excess of 50 psi. If the information on construction of these shelters can be disseminated to the public, and 24 to 48 hours are available for construction, very good protection can be developed for very large numbers of people. For the foreseeable future, this expedient, self-help alternative is all they are likely to have.

Far more people would survive a rapidly-developing nuclear war if shelter were already in place before the onset of a nuclear crisis. One of the major deterrents to a program that would provide shelter for all Americans is its cost which will be the product of the cost per space times the number of spaces needed. In the case of blast shelters, the number of spaces needed is approximately 160 million. Fallout shelter spaces needed are approximately 80 million. Single-purpose, small blast shelters can cost from $500 to $2500 or more per space, with $1000 being representative. Blast shelters built into the basements of new construction can be constructed for $250 to $500 per space, with $300 being a good representative figure. Fallout shelter built into new masonry construction may cost only about $50 per space. Slightly altering new construction to make maximum use of features which would have been constructed in any case, such as basements, is called "slanting." This technique is by far the most cost-effective approach to developing shelter.

Construction with the potential for blast slanting includes basements of masonry buildings with concrete first floors, schools and residences designed partially or wholly underground for energy conservation, aesthetics, or tornado protection, and underground mining operations for the production of concrete aggregate or agricultural limestone.

A shelter program based on blast and fallout slanting in new construction would entail an annual expenditure of approximately

1% (continued over ten or more years) of the annual Department of Defense budget. Funding at this level might be considered if this country were to adopt a defensive strategic posture. However, for the present, while we know how to build shelters, we have not solved the political problem of allocating the resources to get them built.

CONVERSION FACTORS FOR SI UNITS

English units have been retained in the body of this report. The report refers to commercially available materials and sizes commonly expressed in English units. The report reviews earlier work expressed entirely in English units. Conversion factors for SI units are given below:

To convert from:	To:	Multiply By:
atmosphere (14.7 psi)	kilopascal (kPa)	101.325
cubic feet (ft^3 or cu ft)	cubic meter (m^3)	0.0283
foot (ft)	meter (m)	0.3048
footcandle	$lumen/meter^2 (lm/m^2)$	10.764
gallon (gal)	cubic meter (m^3)	0.003785
gravity (32.174 ft/sec^2)	$meter/sec^2 (m/s^2)$	9.80665
inch (in.)	meter (m)	0.0254
mile (mi)	meter (m)	1609.3
pound-force/in^2 (psi)	kilopascal (kPa)	6.8948
quart (qt.)	cubic meter (m^3)	$9.464X10^{-4}$
square foot (ft^2, sq ft)	square meter (m^2)	0.0929
square mile (mi^2)	square meter (m^2)	$2.59X10^6$
ton (nuclear equivalent of TNT)	joule (J)	$4.20X10^9$
ton (2000 pounds)	kilograms (Kg)	907.185

ABSTRACT

The literature on the design, construction, testing, and cost of blast and fallout shelters was reviewed, and a bibliography of over 1000 documents was assembled. It was found that nuclear weapon effects and shelter design are well understood. The definitive state of the art in structural design of blast shelters is comprehensively described in the 1985 update of the American Society of Civil Engineers Manual No. 42, Design of Structures to Resist Nuclear Weapons Effects.

An important barrier to construction of permanent shelters is cost. Single-purpose shelters cost in the high hundreds to low thousands of dollars per occupant (or per space), depending on size, hardness, location, and whether the shelter is part of new construction or retrofit. Multiplied by a risk area population of approximately 160 million, the cost of a blast shelter construction program would rival that of a major strategic weapon system.

Options in the mid-range of expense, a few tens to a few hundreds of dollars per space include (1) requiring modified limestone mining practices, where appropriate, to generate usable shelter space near cities; (2) encouraging the construction of earth-sheltered housing and other buildings; and (3) requiring and/or subsidizing the construction of dual-use basement shelter in new construction. A program using this approach would require an annual expenditure of approximately 1% of the annual defense budget for 10 or more years.

The very low-cost (and less effective) options open to the U.S. government, with its present civil defense budget, remain as follows: (1) maintain the inventory of fallout shelters and identify space with some blast protection potential, (2) plan for "crisis upgrading" to improve existing space in a crisis, and (3) plan for construction of expedient shelters in a crisis. The crisis-implemented options require several days' warning in order to be effective.

While much of the technology for protecting people against nuclear weapons effects originated in this country, we have not solved the political problem of allocating the resources to protect our own population.

CIVIL DEFENSE SHELTERS - 1986
STATE-OF-THE-ART ASSESSMENT

C. V. Chester
G. P. Zimmerman

1. INTRODUCTION

1.1 WHAT ARE WE TRYING TO DO?

This literature review is one of several being sponsored by the Federal Emergency Management Agency (FEMA). The purpose of these reviews is several fold:

1. To summarize in a useful form the most important results of research sponsored by FEMA and its predecessor agencies over the past four decades. In particular, it would provide understanding of the most important results for recently appointed civil defense decision makers.

2. Where appropriate, to identify and highlight results which could be, but are not being, utilized in the present FEMA programs and policies. Results which support (or oppose) the credibility of FEMA programs are examples.

3. To identify important questions which are not addressed by the present body of research and for which answers are needed.

1.2 WHY BOTHER?

In the present (mid-1980s) political and economic climate, investment in a major shelter building program is very unlikely. With the U.S. Congress and the Administration struggling with deficits of $200 billion and attempts to sustain or increase the defense budget, undertaking a program which could lead to expenses in excess of $100 billion to deal with an event considered to be of very low probability is unlikely, so why bother with this study?

- Nuclear weapons are not likely to go away.

- A great deal of money was invested by the Federal government in developing the technology for protecting people against weapons effects. We should try to preserve that technology.

2. NATURAL AND TECHNOLOGICAL THREATS

A discussion of shelter must address the question: "shelter against what?" This study is concerned with shelter from life- or health- threatening conditions in the environment. Although the bulk of the examined literature is concerned with protection against the effects of nuclear weapons, there are a variety of peacetime hazards which can result in large-scale disasters (Federal Emergency Management Agency, 1984). Collins (1972) and Quarantelli (1982) have addressed the problems which accompany sheltering the population after such disasters.

2.1 TORNADOES, HURRICANES, AND HIGH WINDS

Atmospheric, weather-related disturbances produce some of the most spectacular peacetime disasters. They are capable of producing dramatic, local property damage anywhere in the entire United States. An average of 150 fatalities per year are produced by tornadoes which can have winds approaching 300 mph (Abbey, 1976). These short-lived storms are the most violent and destructive of all atmospheric phenomena. Storm cellars and covered dugouts have been traditional fixtures on farms in the U.S. central plains, principally for protection against tornadoes. Fatalities of 150 people per year are trivial compared to the fatalities from automobile accidents; however, the effects of tornadoes are so dramatic that people have made considerable investments in protection against them. Earth-sheltered homes and schools (Defense Civil Preparedness Agency, 1973) in the central region of the United States, from Texas to Minnesota, are quite common. Oklahoma, which is the state that has the highest tornado frequency, is also the state with the largest number of earth-sheltered schools (Oklahoma State Department of Education, 1978).

It is virtually impossible to build a frame residence that will survive a severe tornado. Strong, reinforced concrete buildings provide increased resistance (Defense Civil Preparedness Agency, 1976; Federal Emergency Management Agency, 1980b, 1982). Earth-sheltered housing (see Section 7.5.3), and any other belowgrade structure, is virtually immune to the high winds and the very low internal pressures which are responsible for the destruction of conventional structures. Fallout shelters with 300 lb/ft^2 of concrete or earth covering the roof are likewise unlikely to be damaged by tornadoes.

Hurricane damage is limited to the U.S. coastal regions. Adequate protection from hurricane winds can be provided (Spangler and Jones, 1984), but the possibility of flooding precludes the use of belowground shelters.

2.2 NUCLEAR ACCIDENTS

As events at Chernobyl in April 1986 demonstrated, it is possible for a nuclear reactor to undergo accidents which release large amounts of radioactivity to the environment. While the radioactivity released at Chernobyl was a minute fraction of that expected from a ground-burst megaton weapon, it did result in the evacuation of nearby civilian populations as a precaution. Because of organizational and managerial deficiencies, the surrounding population was not made aware of the seriousness of the accident from some time. Had they been notified, they could have taken shelter in basements, fallout shelter areas, and interior portions of their multifamily dwellings and significantly reduced the gamma radiation dose to which they were exposed. Even the most severe hypothetical reactor accident scenarios postulate environmental contamination which is a very small fraction of that which could be produced by widespread nuclear weapon fallout from a war (Nuclear Regulatory Commission, 1976). Any fallout shelter useful against weapons effects will provide more than adequate protection against external gamma radiation doses from any reactor accident.

2.3 TOXIC AEROSOLS AND VAPOR

Unless equipped with appropriately designed filters, fallout and blast shelters provide very little protection against airborne toxic aerosols and toxic vapors. These toxic materials, whether they are toxic chemical vapors from a Bhopal-like incident, radiological aerosols coming from a damaged nuclear reactor, or chemical or biological weapons disseminated by terrorists, are drawn into the shelter with the ventilation air and breathed by the occupants. Particulate filters are available which will remove any toxic aerosol; charcoal filters are available which will remove moderate amounts of most toxic chemical vapors. The better Swiss shelters are equipped with such filters. Particulate filters are relatively inexpensive and are probably a prudent investment to anyone building a fallout or blast shelter. Charcoal filters are much more expensive and are probably unjustified, unless one is building a shelter downwind of a known chemical hazard.

Protection against toxic aerosols and vapors can be obtained in a well constructed modern house, if it is pressurized by a blower drawing air through a filter effective against the expected toxic agent. The blower capacity must exceed the infiltration rate of the house when the doors and windows are closed. (Some protection against toxic aerosols can be obtained by using a household vacuum cleaner as a blower/filter for this purpose.)

Belowground fallout and blast shelters are more easily protected against toxic aerosols because they generally have much slower (almost zero) infiltration rates with the doors and ventilating openings closed off.

2.4 LARGE FIRES

Fires of external origins such as forest fires or those from aircraft crashes occasionally threaten the general public in residential areas. Human casualties are usually very low but property destruction can be quite extensive. Destruction of residential areas due to wildfires is almost an annual occurrence in the western part of the United States. Earth-sheltered houses, and virtually any underground shelter, provide almost complete protection against this hazard, provided that the air supply to the shelter area is not contaminated by smoke or toxic fumes (Broido and McMasters, 1960; Earp, 1953; Irving, 1964; Miller and Kerr, 1965; and Murakoa, 1961).

Well-designed nuclear shelters provide fire protection at a level which exceeds fire codes. This is because fire codes assume the continuing availability of professional fire fighters and a reliable water supply, while the lack of such services must be assumed in survival shelter construction (Murphy, Rempel, and Beck, 1975).

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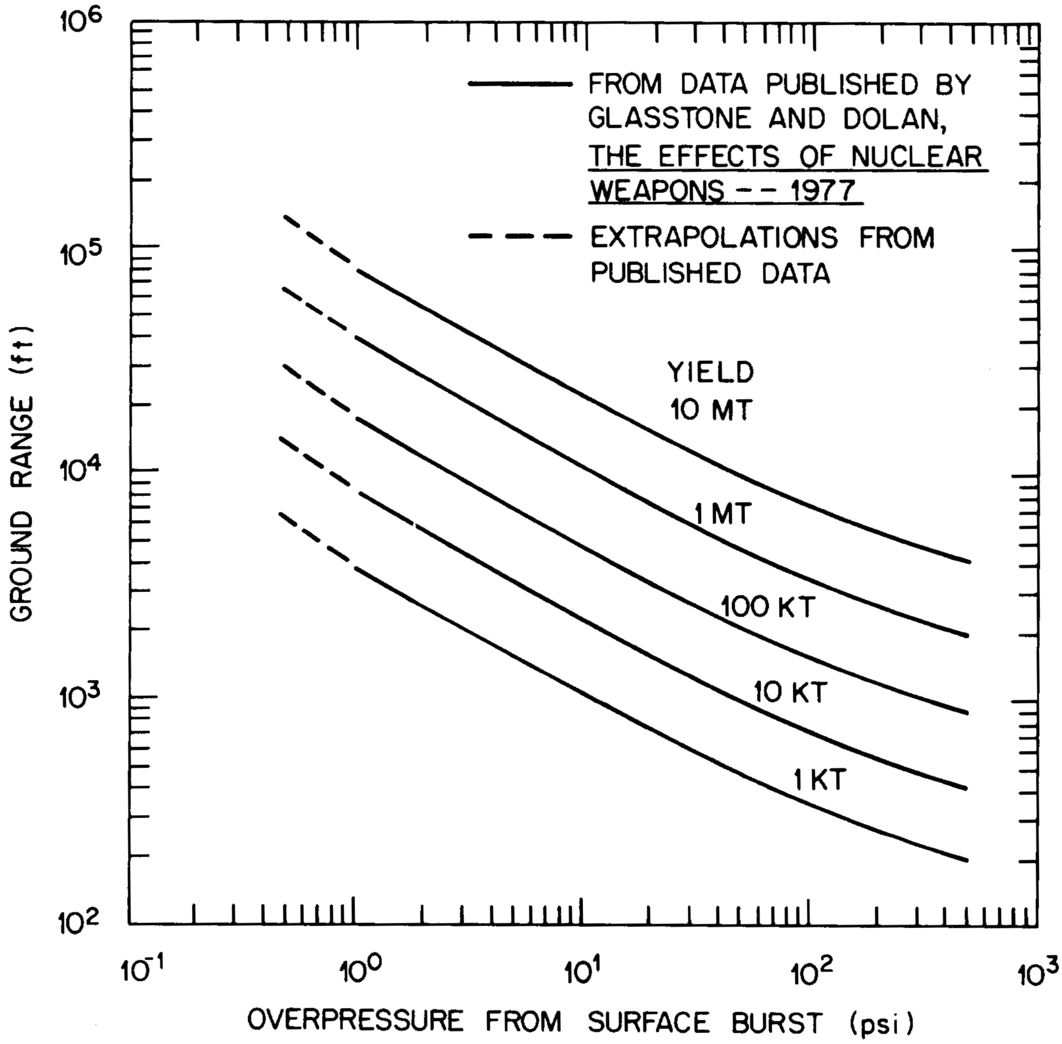

Fig. 3.1. Weapon overpressure as a function of distance from a surface burst.

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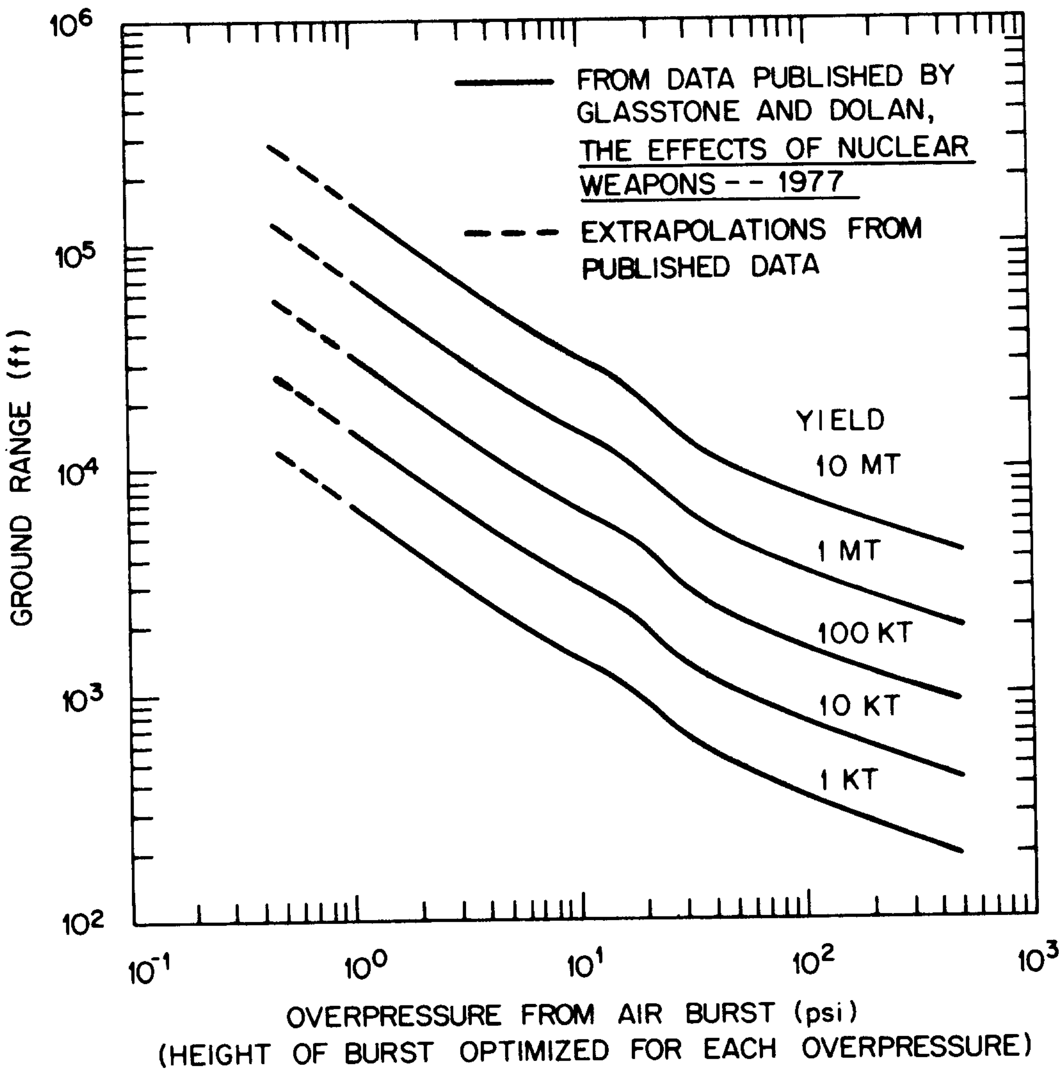

Fig. 3.2. Weapon overpressure as a function of distance from the ground zero of an airburst.

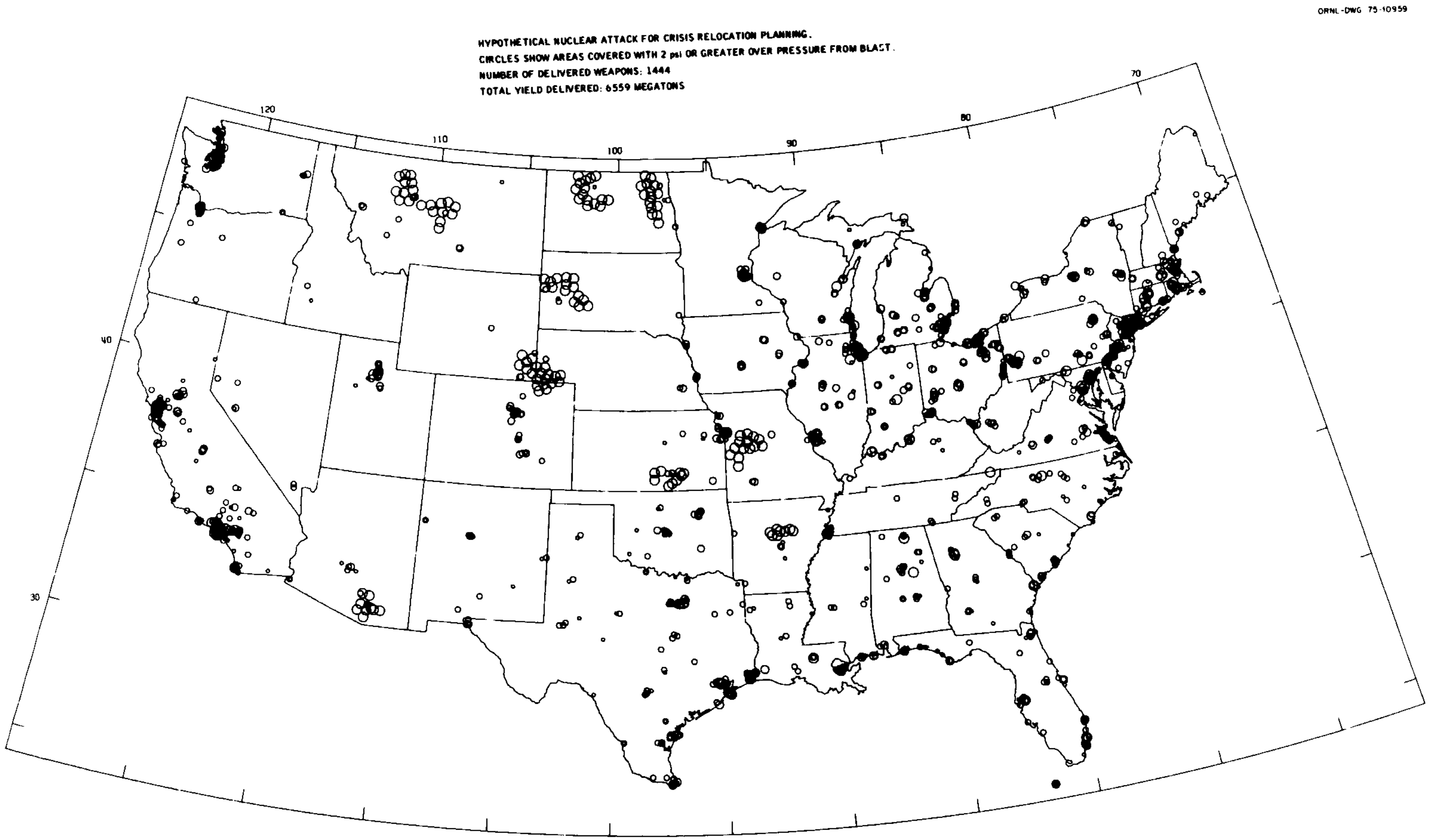

Fig. 3.3. Hypothetical attack pattern on the United States.

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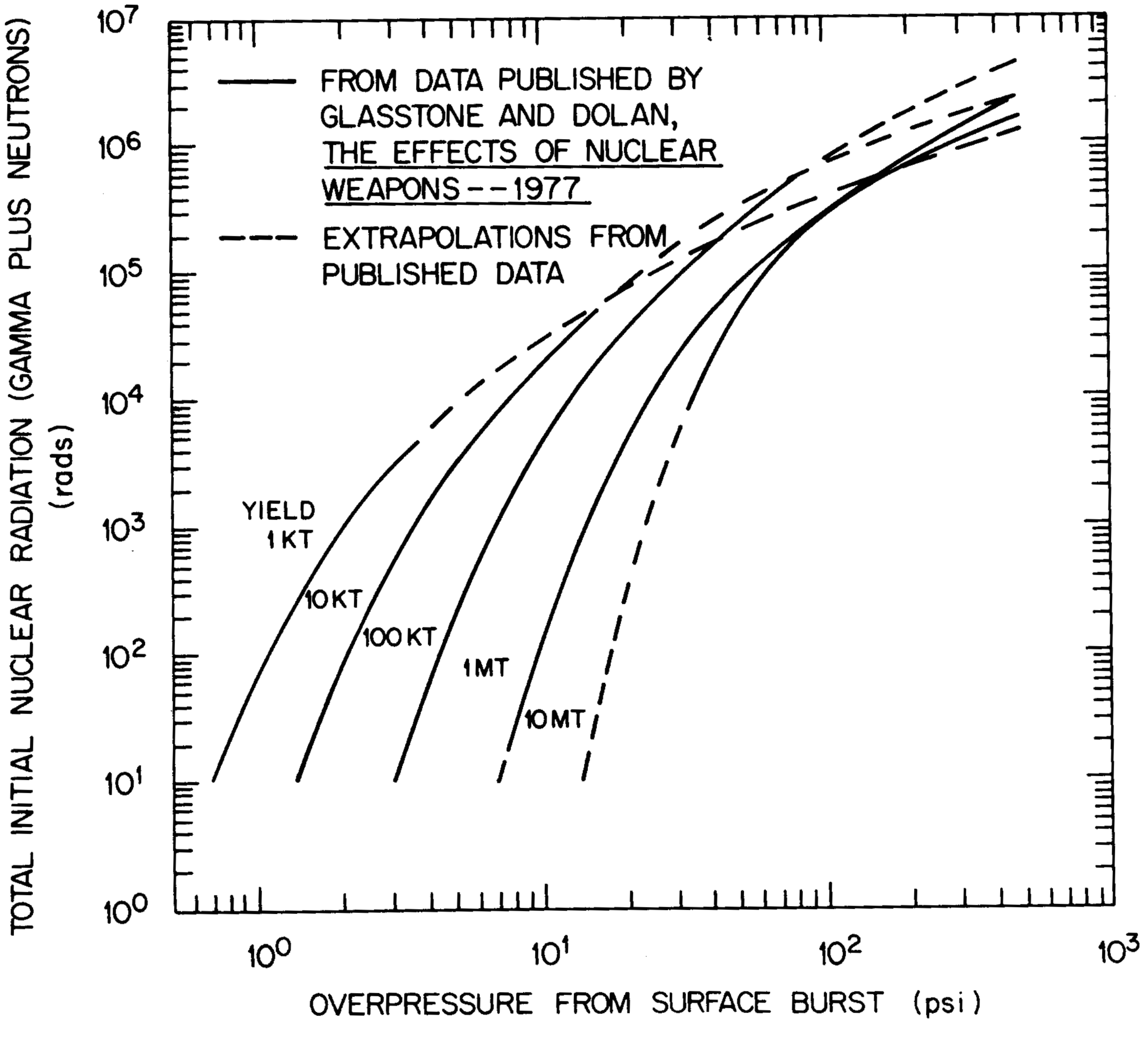

Fig. 3.4. Initial nuclear radiation as a function of overpressure from a surface burst.

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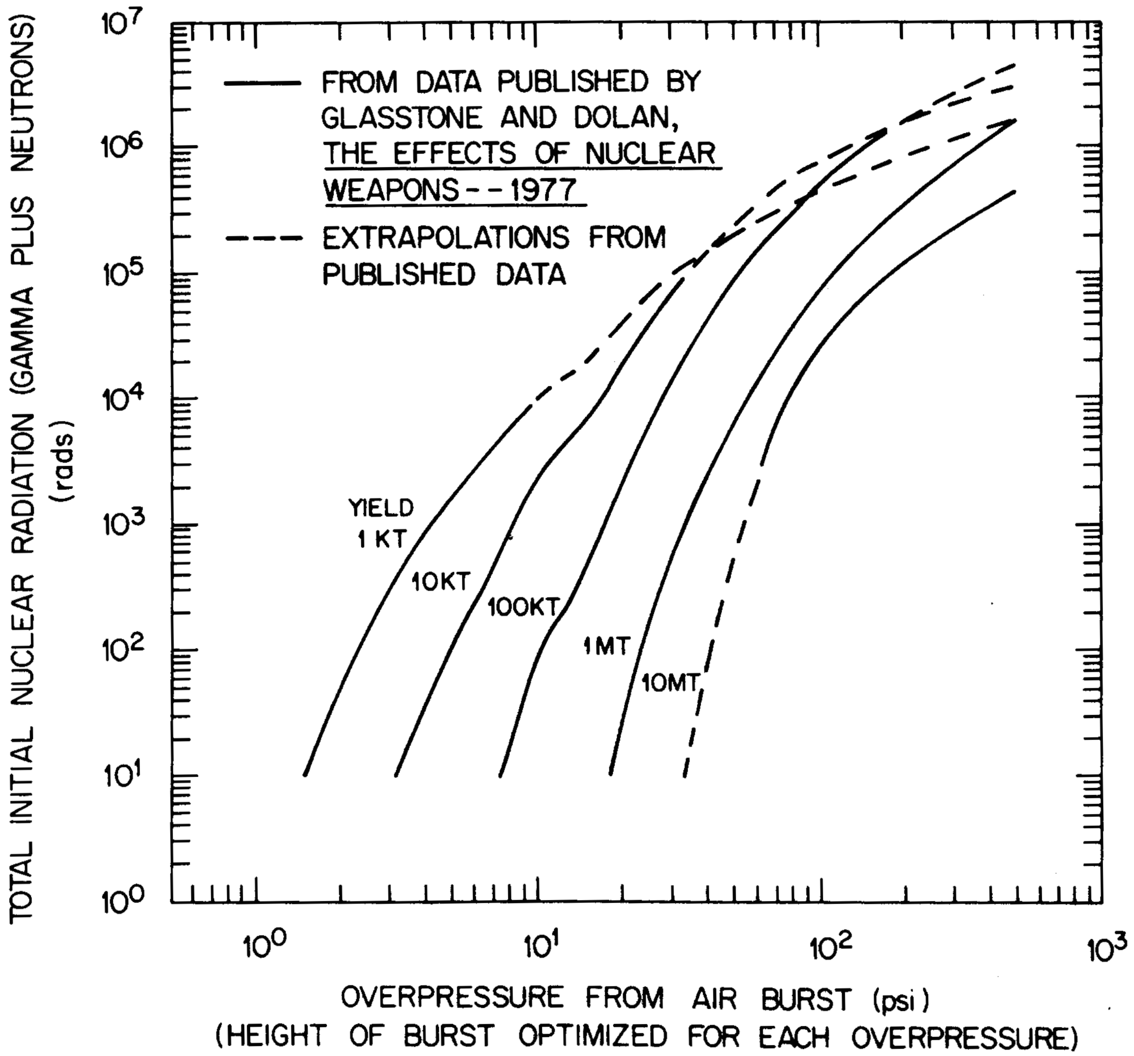

Fig. 3.5. Initial nuclear radiation as a function of overpressure from an airburst.

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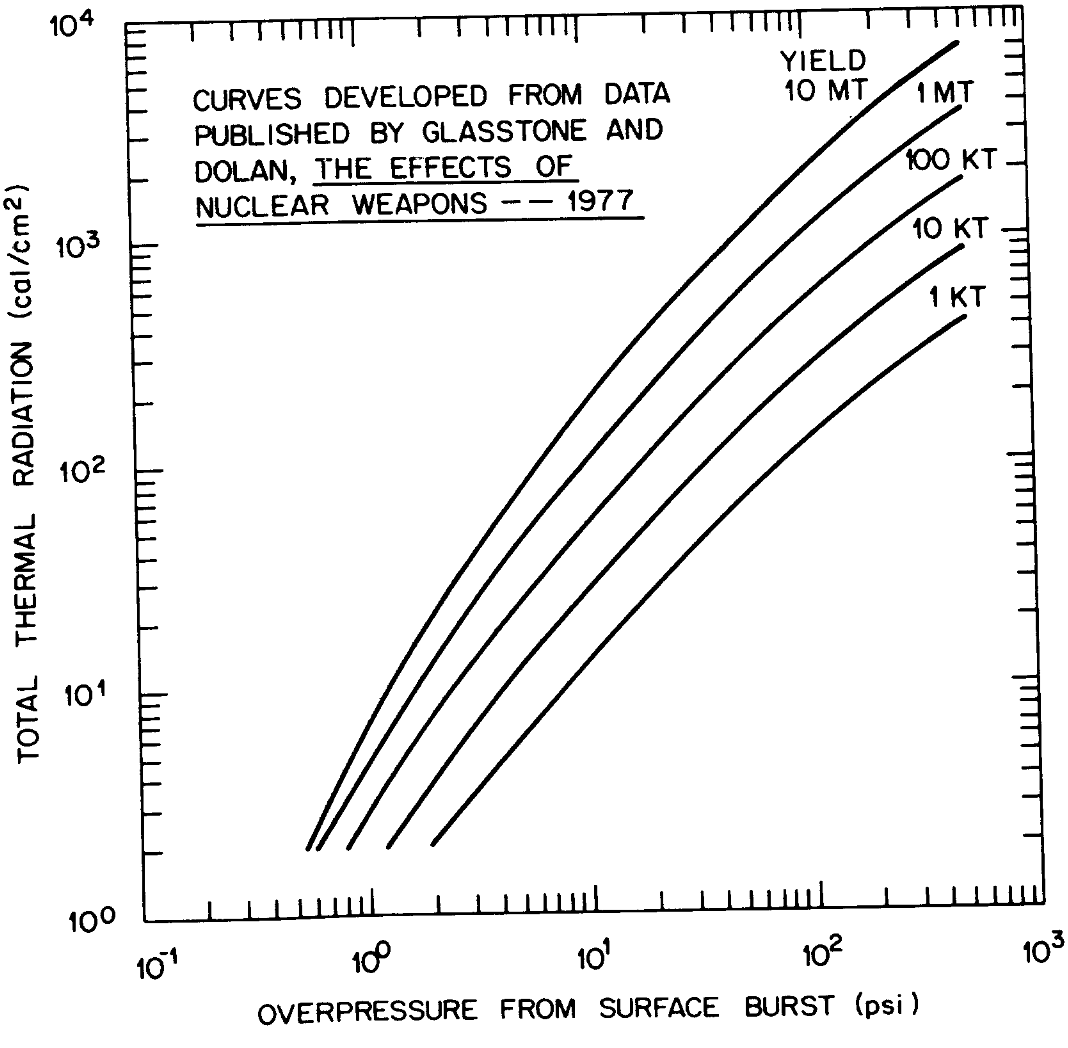

Fig. 3.6. Thermal fluence as a function of overpressure from a surfaceburst on a clear day.

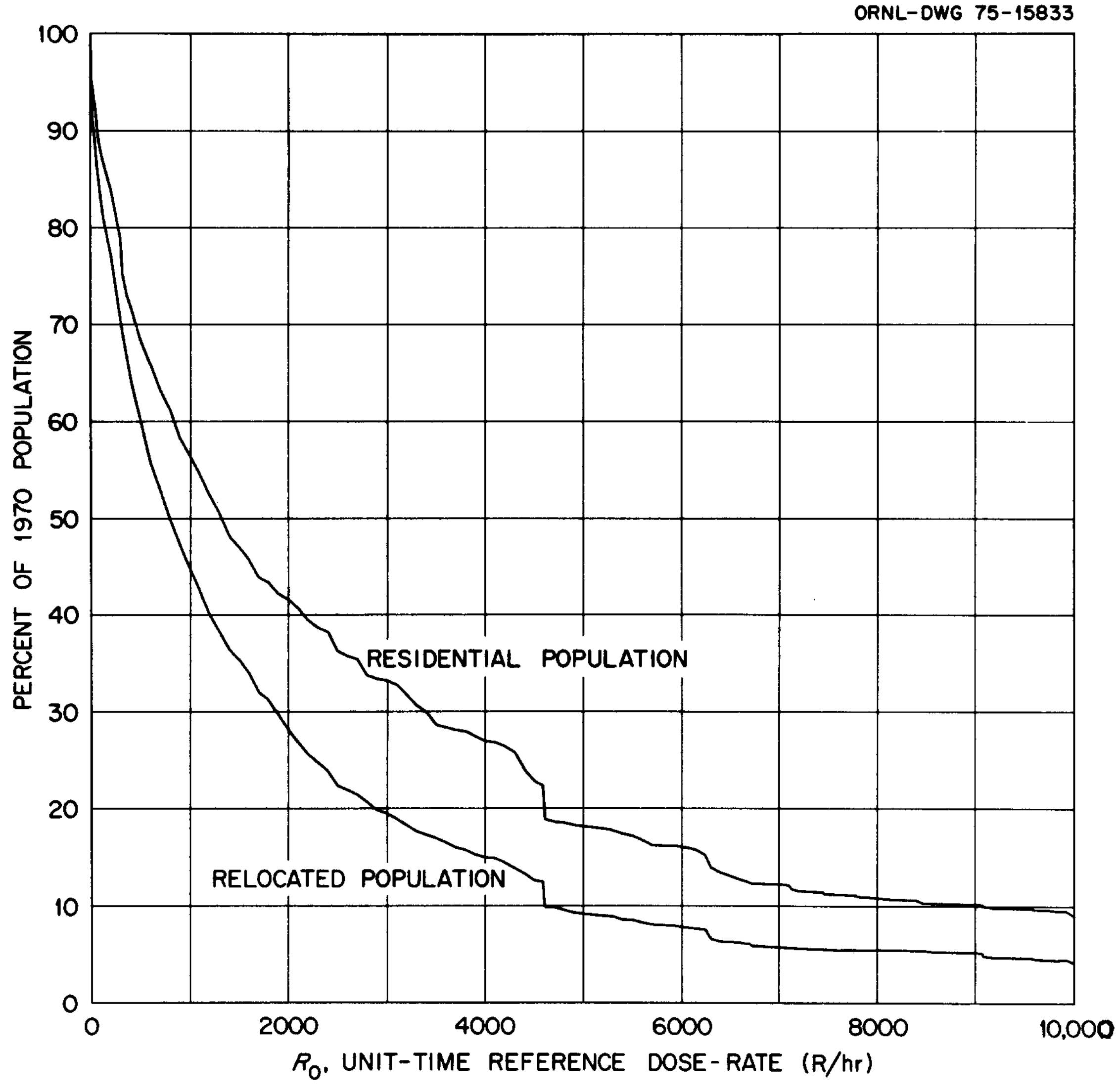

Fig. 3.8. Cumulative population exposed as a function of fallout radiation dose rate.

Table 4.1. Initial radiation dose (R) in a fully buried basement with varying concrete thickness of the first floor

Weapon yield/ Overpressure	Initial radiation dose (R) inside shelter with a floor thickness of (inches)				
	12	14	16	18	24
1 MT, 20 psi	47	29	19	12	5
1 MT, 30 psi	166	104	70	46	17
100 kT, 20 psi	284	189	130	88	30
200 kT, 30 psi	974	658	457	310	104

SOURCE: Strope et al., 1985.

4.2.2 Geometry Shielding

The difficulty of calculating the radiation protection offered by a shelter space involves more than just the complexity of the radiation energy spectrum, the type of radiation, and its interaction with different types of matter. It also involves the nonuniformity of the shielding, because the arrangement of barrier shielding around the shelter volume is, in general, not of uniform thickness.

The technique of analysis involves dividing the shield into fairly uniform sections and calculating what fraction of the radiation gets through each element of the shield. The penetration of each element is by engineering estimation for mass thicknesses or by computer or hand calculations.

Convenient graphical techniques exist for doing these calculations. Figure 4.3 is a graphical method of estimating the solid angle subtended by a rectangular element. The solid angle is often expressed as the fraction of a hemisphere surrounding the detector. To determine the total exposure at some point inside the shelter, the solid angle subtended by each element of the shield is calculated and multiplied by the radiation coming through each element; then, the whole is added up to get the total amount of radiation entering the protected space.

The literature on radiation shielding is very large. The literature on shielding of people by shelters is only slightly less large. Much of it was generated in the nuclear weapons tests in the 1950s, but a great deal was done with fallout simulation and calculation in the 1960s and 70s. The data that were developed in that time have been reduced to relatively simple graphical calculation techniques available in the various shelter handbooks and in shielding manuals. (Abbott, 1973; Beer and Cohen, 1975; Cain, 1964; Defense Civil Preparedness Agency, February1976, February 1978; Donovan and Chilton, 1961; Eisenhauer, 1964; Federal Emergency Management Agency, September 1980, 1981; LeDoux and Donovan, 1961; McDonnell and Velletri, 1966; Martin and Latham, 1963; Owen, 1962; Spencer, 1962; Spencer, Chilton, and Eisenhauer, 1980; Spring and McDonnell, 1967).

For very complex geometries where much more accuracy is desired, large computer calculations using fairly elaborate shielding codes can be employed. The Radiation Shielding Information Center at the Oak Ridge National Laboratory is the national repository of all shielding codes developed in this country and in most of the western world.

For additional information on structure shielding from both fallout and initial nuclear radiation, the following references are suggested: American Institute of Architects (1970); Beer and Cohen (1973); Brusse (1964); Burson (1963); Burson and Borella (1961); Cameron and Huff (1962); Clarke, Batter, and Kaplan (1959); Defense Civil Preparedness Agency (November 1972b, 1977, September 1978): Federal Emergency Management Agency (July 1982, September 1983); French, Price, and Tompkins (1965); Haaland (1983); Holmes and Narver, Inc. (1965b); Hubbell and Spencer (1964); Huddleston, Doty, and Ingold (1968); LeDoux (1959, 1960); McDonnell and Velletri (1967); Reynolds, Faw, and Robinson(1971); Robinson, Reynolds, Burre, and Faw (1969); Schmoke and Post (1974); Starbird, Velletri, MacNeil, and Batter (1963).

4.3 ENTRANCES, EXITS, AND CLOSURES

This section is concerned with entrances, exits, and closures for belowground civilian blast shelters designed for overpressures generally under 100 psi.

4.3.1 Entrances

Entrances must be constructed so that people can get into the shelter as efficiently (quickly) as possible and so that blast overpressure and radiation (especially initial nuclear radiation) will be kept out of the shelter--all this must be done at the least possible cost. The most effective techniques for accomplishing these objectives are fairly well understood.

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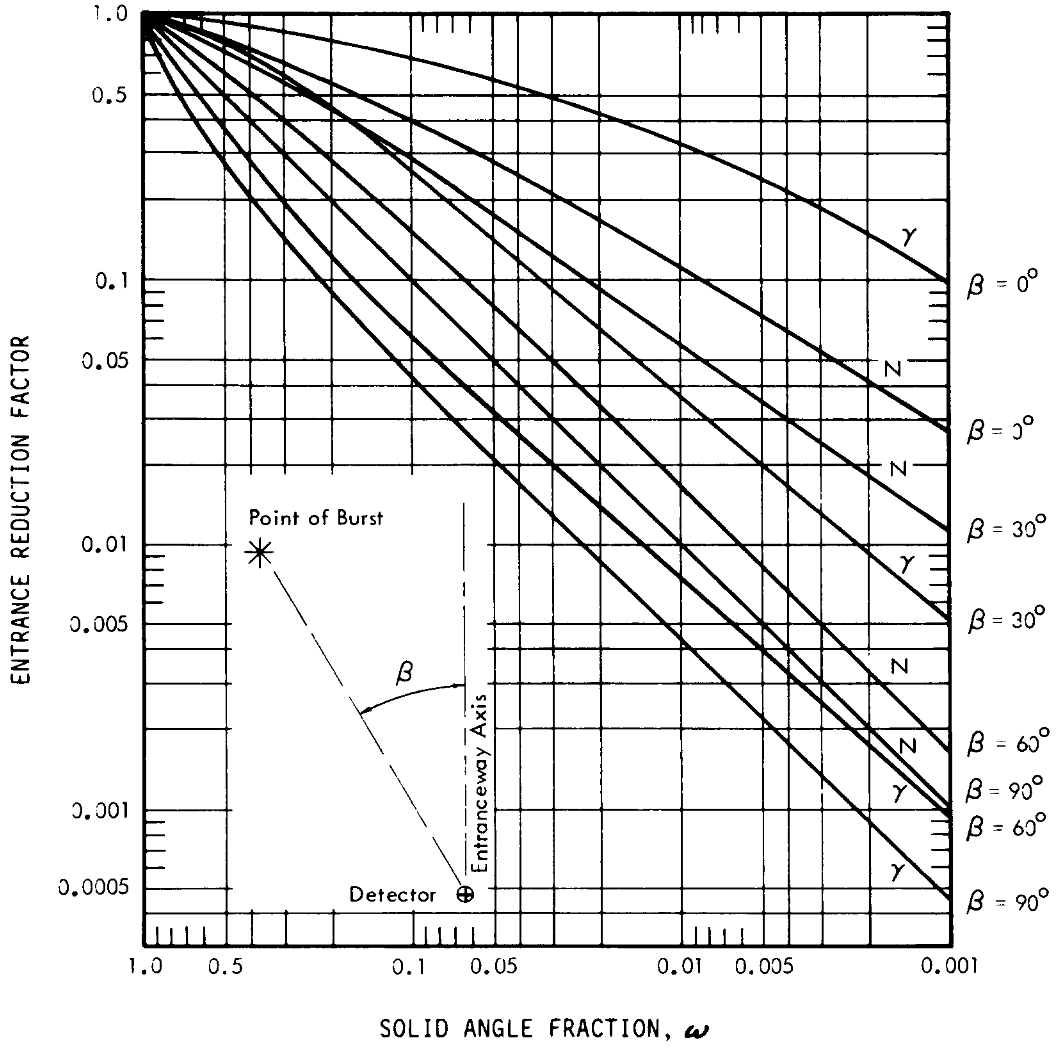

(N = Initial Neutron Radiation; γ = Initial Gamma Radiation)

Fig. 4.4. Entrance reduction factor for initial nuclear radiation.

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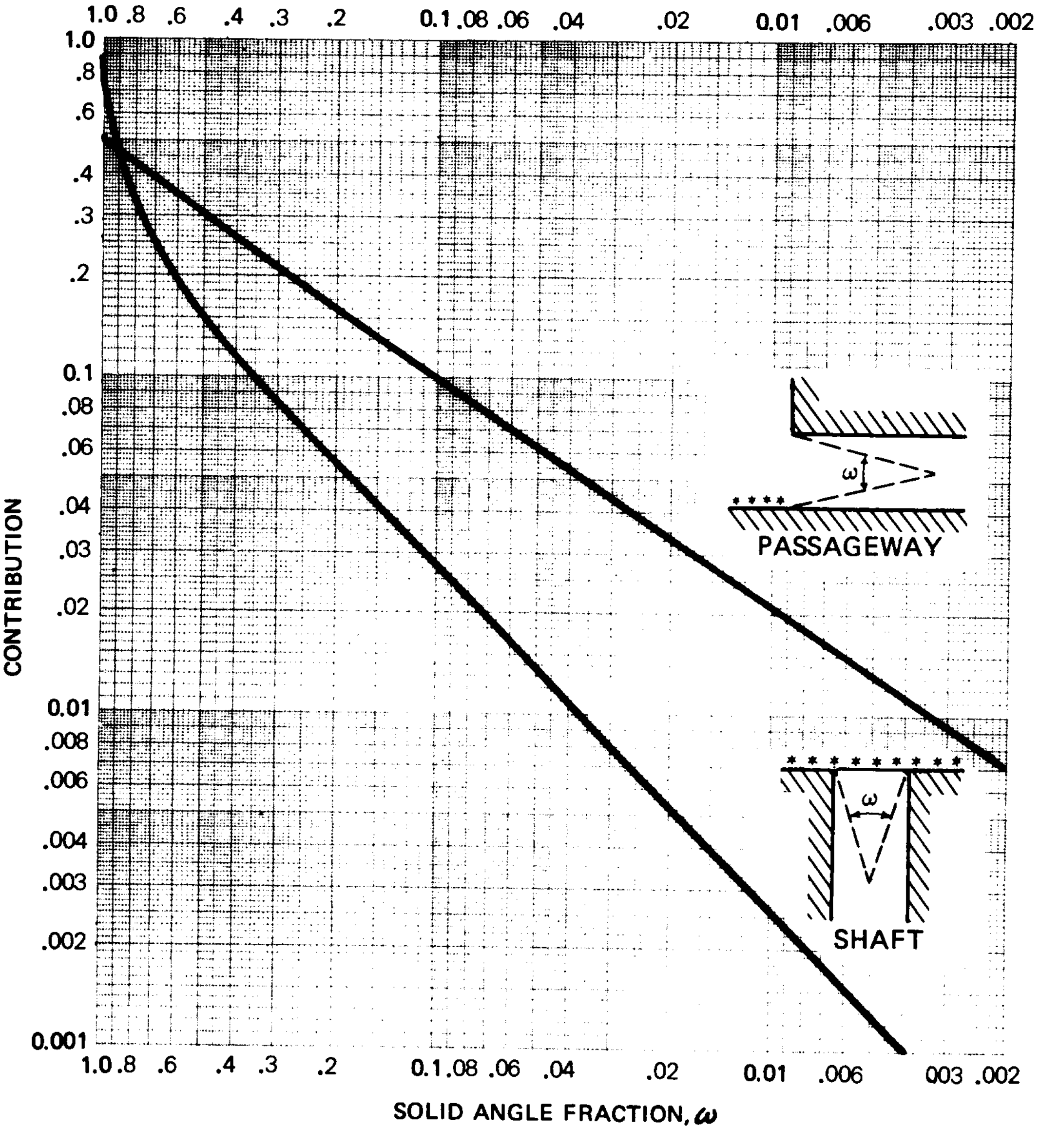


Fig. 4.5. Entrance reduction factor for fallout radiation.

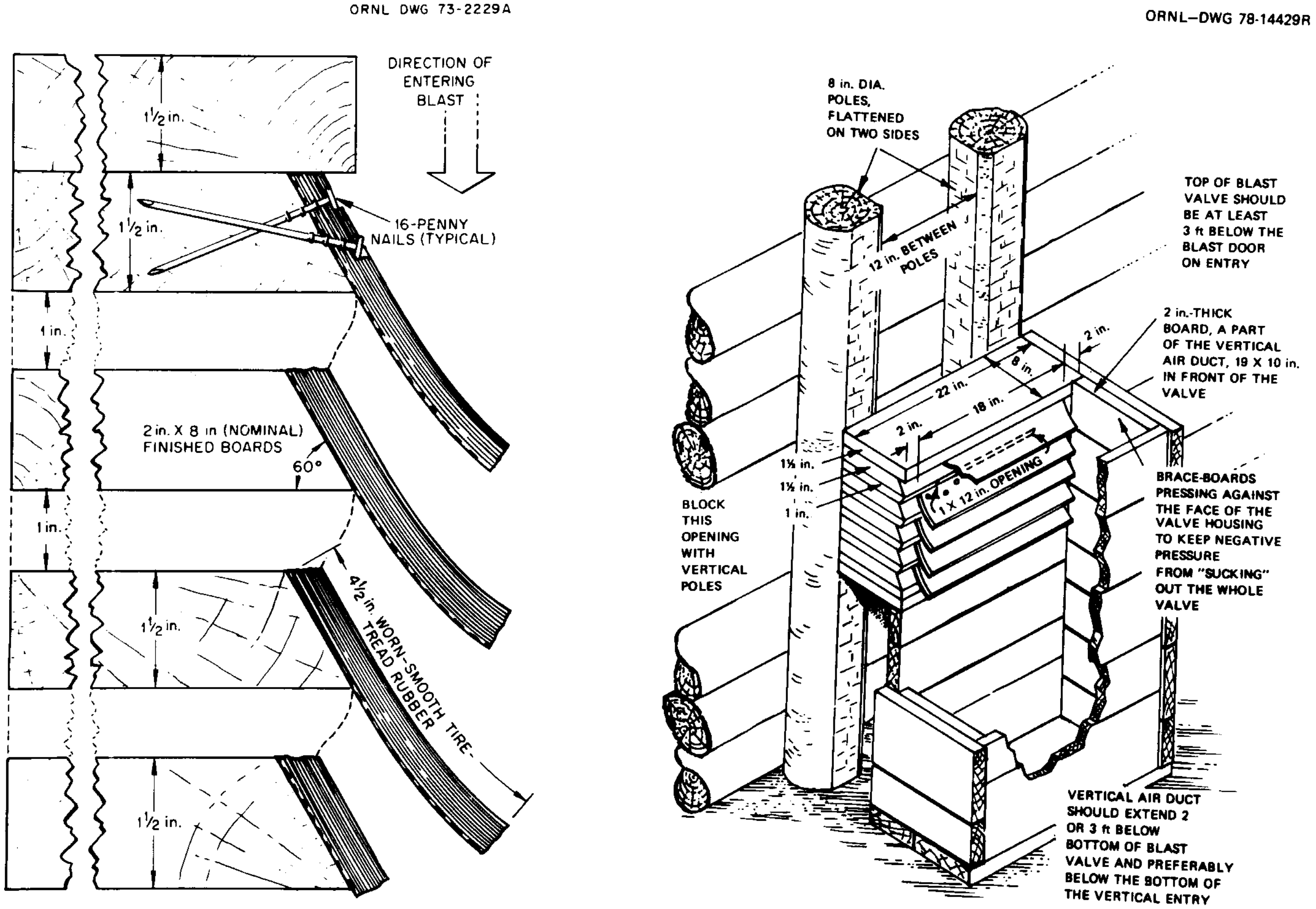


Fig. 4.16. Kearny blast valve.

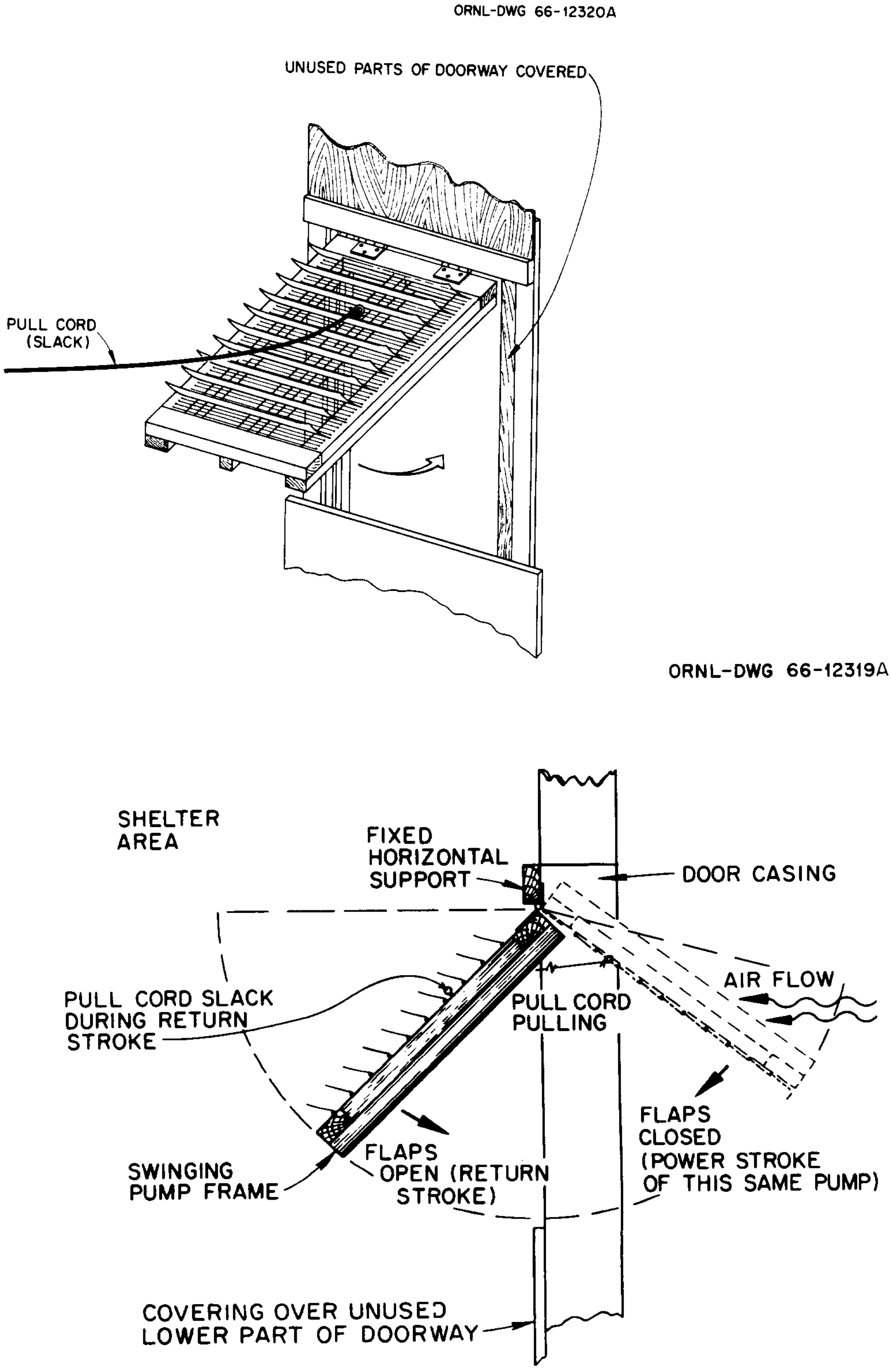
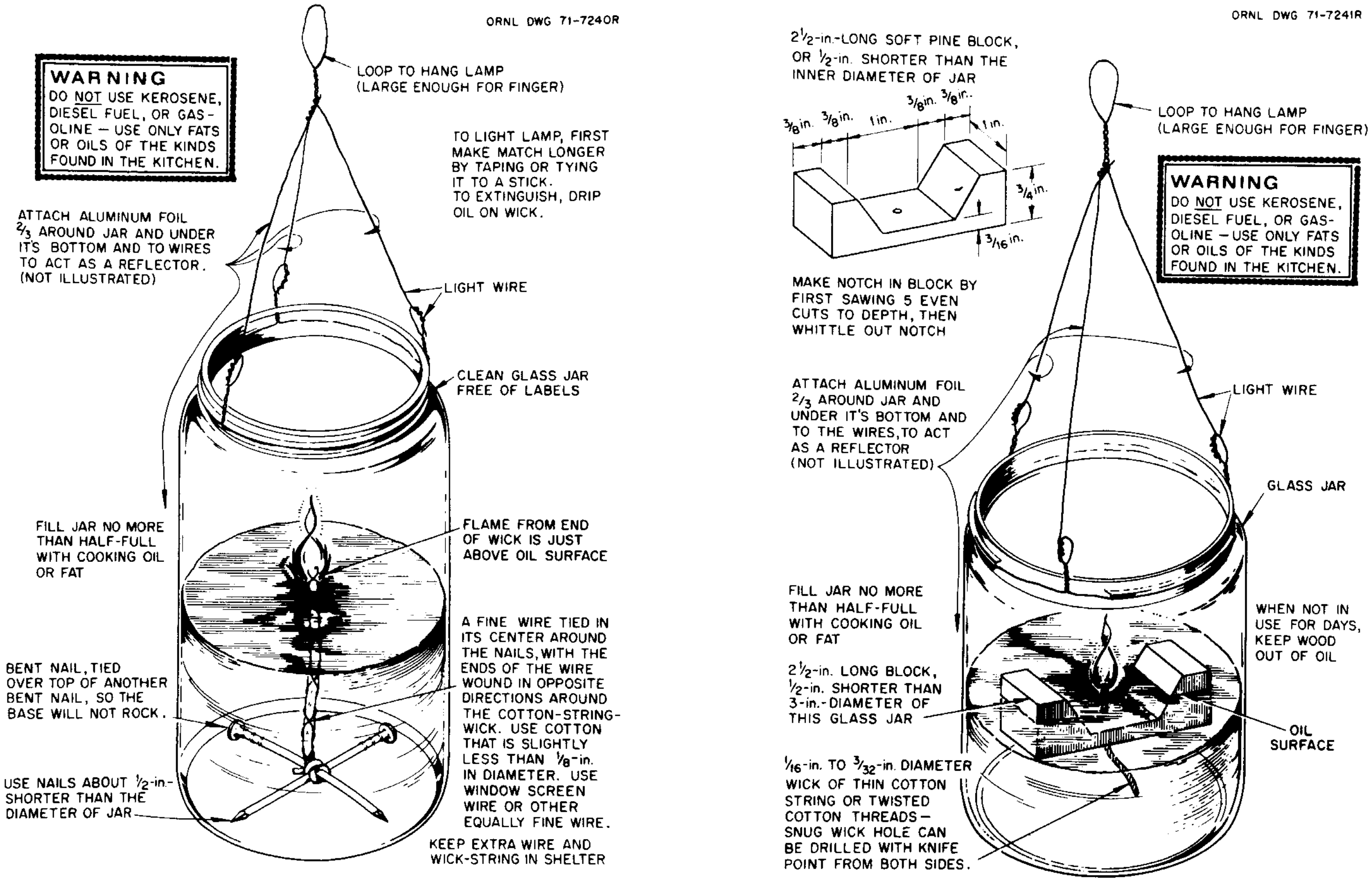


Fig. 4.19. Kearny air pump.



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WARNING
DO NOT USE KEROSENE, DIESEL FUEL, OR GASOLINE – USE ONLY FATS OR OILS OF THE KINDS FOUND IN THE KITCHEN.

LOOP TO HANG LAMP (LARGE ENOUGH FOR FINGER)

TO LIGHT LAMP, FIRST MAKE MATCH LONGER BY TAPING OR TYING IT TO A STICK. TO EXTINGUISH, DRIP OIL ON WICK.

ATTACH ALUMINUM FOIL 2/3 AROUND JAR AND UNDER ITS BOTTOM AND TO WIRES TO ACT AS A REFLECTOR. (NOT ILLUSTRATED)

LIGHT WIRE

CLEAN GLASS JAR FREE OF LABELS

FILL JAR NO MORE THAN HALF-FULL WITH COOKING OIL OR FAT

FLAME FROM END OF WICK IS JUST ABOVE OIL SURFACE

A FINE WIRE TIED IN ITS CENTER AROUND THE NAILS, WITH THE ENDS OF THE WIRE WOUND IN OPPOSITE DIRECTIONS AROUND THE COTTON-STRING-WICK. USE COTTON THAT IS SLIGHTLY LESS THAN 1/8-in. IN DIAMETER. USE WINDOW SCREEN WIRE OR OTHER EQUALLY FINE WIRE.

BENT NAIL, TIED OVER TOP OF ANOTHER BENT NAIL, SO THE BASE WILL NOT ROCK.

USE NAILS ABOUT 1/2-in.-SHORTER THAN THE DIAMETER OF JAR

KEEP EXTRA WIRE AND WICK-STRING IN SHELTER

WIRE-STIFFENED-WICK LAMP

ORNL DWG 71-7241R

2 1/2-in.-LONG SOFT PINE BLOCK, OR 1/2-in. SHORTER THAN THE INNER DIAMETER OF JAR

LOOP TO HANG LAMP (LARGE ENOUGH FOR FINGER)

WARNING
DO NOT USE KEROSENE, DIESEL FUEL, OR GASOLINE – USE ONLY FATS OR OILS OF THE KINDS FOUND IN THE KITCHEN.

MAKE NOTCH IN BLOCK BY FIRST SAWING 5 EVEN CUTS TO DEPTH, THEN WHITTLE OUT NOTCH

ATTACH ALUMINUM FOIL 2/3 AROUND JAR AND UNDER IT'S BOTTOM AND TO THE WIRES, TO ACT AS A REFLECTOR (NOT ILLUSTRATED)

LIGHT WIRE

GLASS JAR

FILL JAR NO MORE THAN HALF-FULL WITH COOKING OIL OR FAT

WHEN NOT IN USE FOR DAYS, KEEP WOOD OUT OF OIL

2 1/2-in. LONG BLOCK, 1/2-in. SHORTER THAN 3-in.-DIAMETER OF THIS GLASS JAR

OIL SURFACE

1/16-in. TO 3/32-in. DIAMETER WICK OF THIN COTTON STRING OR TWISTED COTTON THREADS – SNUG WICK HOLE CAN BE DRILLED WITH KNIFE POINT FROM BOTH SIDES.

FLOATING WICK LAMP

Fig. 4.20. Safe expedient lamps.

All of the shelter tests that were conducted by the United States during actual nuclear detonations are summarized in Nuclear Weapons Effects Tests of Blast-type Shelters by Christian Beck (1969). This volume is a compendium of all of the individual weapons test reports on blast shelters.

The first documented tests of U.S. shelters occurred in the BUSTER-JANGLE test series in Nevada during October and November of 1951. In these tests some 29 shelters were built along an arc about 1200 ft from the designated ground zeros of three low-kiloton airbursts. The shelters were wood-lined covered trenches, covered metal arches, and basement lean-to shelters. Instrumentation was very crude. The tests showed that very low-cost structures, when covered with soil, could resist nuclear weapons effects (Flynn, 1952). Tests of buried concrete and steel pipe showed that economical structures could be built to resist a great deal of blast pressure and to provide significant radiation protection (Corsbie, 1952).

In the Nevada TUMBLER-SNAPPER series in April through June 1952, "hasty air-raid shelters" were tested; these were unshored, covered trenches exposed to low-kiloton nuclear weapons. They provided good radiation protection, but their ability to withstand destruction depended on the cohesiveness of the original soil (Murdock, 1953).

In the UPSHOT-KNOTHOLE series in Nevada during early 1953, instrumentation began to become more sophisticated, producing pressure-time traces. This series included a test of blast effects on entrances and air intakes, including blast valves (Sinnamon, Austin, and Newmark, 1955). Newmark and Sinnamon (1954) carried out some of the first tests on dynamic soil stress in the vicinity of a buried structure. The structure had a very stiff roof and showed no earth-arching. They observed greatly reduced pressure on the walls of the structure and a pressure distribution over the floor comparable to that on the roof.

In this same test series, the Navy tested a bermed 25-ft-span by 48-ft-long steel arch personnel shelter with 3 ft of earth cover at 10.8 psi. The entryway was blown into the shelter by pressure coming down the entrance tunnel. However, the main part of the structure survived with only minor distortion. A structure of similar size, assembled from precast concrete panels, survived with similar, minor damage (Longmire, 1955).

Eight outdoor and four indoor home shelters proposed by the Federal Civil Defense Administration for protection against radiation and blast effects were also tested. The overpressures were about one-half those anticipated, resulting in no damage to any of the shelters. The shelters included a covered trench with concrete liner, a wood-covered trench, a concrete pipe, a block wall, and a wooden basement lean-to. The shelter closest to ground zero survived 25 psi (Brynes, 1953).

Also in the UPSHOT-KNOTHOLE test series, Roberts, White, and Chiffelle (1953) obtained some of the first information on the biological effects of nuclear weapons upon animals and dummies in group shelters.

OPERATION CASTLE in 1954 was a series of high-yield explosions in the Pacific at Bikini Atoll, involving tests of the early thermonuclear weapons (hydrogen bombs). Tests of civilian structures were reported in this series; however, the first shot of the series, BRAVO, had a yield of 14.5 megatons when only a 6-megaton yield was anticipated. The high yield resulted in unanticipated high pressures which caused destruction of structures not directly involved with the tests; failure of protective structures for camera mounts, among other things, were observed (Christensen, 1955).

In OPERATION TEAPOT, in 1955 at the Nevada test site, attempts to get quantitative information on earth-arching using a steel beam roof on an underground shelter were again unsuccessful, probably due to the fact that the structure was too rigid (Woodring, Sinnamon, and Newmark, 1957). Further tests of 25-ft-span by 48-ft-long steel arch shelters were carried out. There were two full-scale structures and three steel and three aluminum quarter-scale models in the test. The buildings collapsed at 30 psi overpressure (approximately 200 psi dynamic pressure). The buildings were bermed aboveground and hence were sensitive to the dynamic pressure (Vaile and Mills, 1956).

Two buried, concrete box shelters with 12- to 24-in. walls were subjected to the effects of an underground nuclear explosion in this series. Both structures survived the blast; although, one was only 55 ft from the lip of the crater and was displaced almost 2 ft vertically and 4 ft radially from ground zero (Sinnamon, Woodring, Newmark, and Matsuda, 1957).

A variety of family shelters were tested in the APPLE-1 and APPLE-2 shots of this series. They included basement exit shelters, masonry shelters, poured-in-place concrete shelters, a basement lean-to, a basement concrete room, a concrete bathroom, and what was called a utility shelter (an aboveground, unbermed, unshielded, cubicle). In general, the underground shelters fared fairly well. The basement exit shelters suffered moderate-to-severe damage depending on the number and size of the shelter openings. The indoor shelters survived quite well at 5 psi despite the fact that the house around them was destroyed (Vortman, 1957).

During the APPLE-2 shot, ten typical American residential structures (houses) of wood, brick, lightweight reinforced concrete block, and lightweight precast concrete slabs were tested. Both one- and two-story structures were subjected to a 29-kT explosion. The two-story brick house and the one-story frame rancher were completely destroyed at the 5 psi overpressure location. The other structures sustained considerable damage, even at overpressures as low as 2 psi (Randall, 1961).

Also, in OPERATION TEAPOT a variety of animals were exposed to blast overpressure and thermal radiation in open shelters. This work contributed much to the understanding of blast biology; it demonstrated the necessity for having doors on blast shelters (White, C.S., et al., 1956).

OPERATION PLUMBBOB took place in Nevada during the summer of 1957. Progressively more sophisticated varieties of shelters were tested in this series. Four concrete arch structures with 16-ft spans and wall thicknesses of 8 in. were placed at expected 50, 100, and 200 psi levels from a 36-kT tower shot. The actual overpressures received were 56, 124, and 199 psi. All structures survived, with some cracking in the structure at the 199-psi pressure level. These structures were placed with the top of the crown 4 ft below ground level so they were effectively protected against drag forces (Flathau, Breckenridge, and Wiehle, 1959).

In the same shot there were tests of 10-gauge corrugated steel cattle passes, 10-gauge corrugated steel circular pipe, and circular concrete sewer pipe. The structures were buried at depths of 5 to 10 ft. Pressures as high as 149 psi and gamma neutron doses in excess of 100,000 R were experienced aboveground at the shelter location; however, there was negligible deflection in all of the shelters and negligible radiation recorded inside (Albright, LeDoux, and Mitchell, 1960).

Two types of 25-ft-span by 48-ft-long corrugated steel arches were also tested in the PLUMBBOB Series. One was a 10-gauge corrugated steel arch, the other was a corrugated steel arch with reinforcing I-beam ribs. Both structures were buried with the crown 5 ft below the original grade. They respectively survived 60 and 100 psi incident pressure (Albright, Beck, LeDoux, and Mitchell, 1961). In another test, a 7-ft-diam, 10-gauge, galvanized, multiplate corrugated culvert buried with 10 ft of earth cover survived a 245 psi incident overpressure. The lack of deformation indicates that it would have survived a much higher overpressure (Williamson and Huff, 1961).

During OPERATION PLUMBBOB, Bultman, Sevin, and Schiffman performed tests on seven existing structures which were left from previous nuclear tests. The primary objective of these tests was to determine the reliability of damage prediction schemes; however, a secondary finding was more important with respect to shelter design. When testing the same underground structures used by Newmark and Sinnamon (1954) in the UPSHOT-KNOTHOLE series, a significant attenuation of effective vertical earth pressure was observed within the first few feet of depth. This was, at last, a clear indication that increasing the depth of burial would provide greater protection from blast loading for buried structures.

In another test, an experiment was done in which a buried vertical concrete cylinder was protected from ground motion by surrounding it with square glass bottles. A reduction of peak acceleration by 75% was observed (Vaile, 1960).

A 7500-ft^2 underground parking garage equipped with a 4-ft-thick rolling door was tested at approximately 40 psi. There was no damage to the garage or to the door. The retaining wall at the end of the entrance ramp was damaged due to 180 psi reflected pressure at that point and to possible pressure amplification in the reentrant corner (Cohen, Laing, and Bottenhofer, September 1962).

The FCDA Family Shelter Mark I was tested at 30, 48, and 65 psi; this shelter was a rectangular concrete box with a "Z" shaped entryway and was designed for 30 psi. There was no damage to the shelter structure at 65 psi. The ventilation pipes were bent over at right angles, thus rendering them inoperative. FitzSimons (1957) estimated that the shelter would have taken considerably more overpressure.

FitzSimons (1958) also tested several industrial doors designed for blast resistance to reflected pressures of 9 to 17 psi. The door types included steel plate, cellular steel, wood plank, hollow plywood, and solid plywood. Only the hollow plywood door failed structurally. The door hardware (i.e., hinges and latches) was found to be the weak point for some of the door designs; the "rebound" forces on the hinges and latches were found to be one-half the positive blast forces on the door.

A concrete and steel bank vault was tested in the PLUMBBOB series at more than 300 psi. The structural integrity of the vault was maintained; although, an outer layer of reinforcing steel was stripped away on one side (Cohen, Laing, and Bottenhofer, May 1962).

A cylindrical concrete personnel shelter developed by the French was tested at 118 and 132 psi. Although superficial damage was done to the structure, radiation protection of the occupants would have been adequate. The intake and exhaust stacks were sheared off (Cohen and Dobbs, 1960). A similar test was run on rectangular buried reinforced concrete and circular reinforced concrete shelters designed by the Federal Republic of Germany. All structures performed as expected (Cohen and Bottenhoffer, 1962).

OPERATION PLUMBBOB also provided an opportunity to test shelter ventilation systems. Dennis, Billings, and Silverman (1962) evaluated the effects of blast on filtration devices and typical gas cleaning equipment. White, Wetherbe, and Goldizen (1957) investigated 18 underground structures for the occurrence of posttest dust. They found that, even in closed shelters, annoying or irritating dust could be produced from the interior surfaces of the shelter as it responded to the blast loading.

OPERATION HARDTACK in 1958 was the last atmospheric nuclear test series at which there was documented testing of civilian shelters. Phase I, employing large-yield weapons, was carried out in the Pacific. The 25-ft-span by 48-ft-long, 10-gauge corrugated metal arches which were tested successfully in the PLUMBBOB series were tested again at the Pacific test site. Two important modifications were made. Due to the high water table, the arches were constructed at grade level and then covered with an earthen berm. The second and more crucial difference is that the berm was composed of coral sand containing large numbers of small crushable sea shells. The arches were tested at pressures ranging from 78 to 180 psi. All failed catastrophically (LeDoux and Rush, 1961).

The OCDM family fallout shelter was tested in Phase II of OPERATION HARDTACK at the Nevada test site. It was expected to have only 5 psi blast resistance, but withstood 13.5 psi with no structural damage at all. With over 2 ft of earth cover on the 8-ft-span roof, it could have taken considerably more overpressure (Roembke, 1958b).

Also in OPERATION HARDTACK, Cameron and Huff (June 1962) tested the initial nuclear radiation doses and the accelerations inside four shelters. Initial nuclear radiation doses were found to be higher than those predicted; however, radiation backscatter from the shelter walls and gamma radiation originating from neutron penetration of the concrete structure were not taken into account in the predictions. Measured accelerations inside the structure indicated that the peak horizontal and peak vertical accelerations were about equal; although, both were up to 50% higher than the free-field accelerations.

If one reviews the history of shelter development in nuclear tests over the period of 1951 to 1958, progress is readily apparent. It was quickly learned that protection from initial nuclear radiation was a major problem which dominated the shelter design for low-yield weapons. It was also learned from animal experiments that it is not possible to build an open shelter for nuclear weapons for more than a few psi. Much effort in the civilian shelter development program was directed at keeping costs down. Helpful in this respect was the use of selected unsaturated soil cover to gain earth arching, thereby helping the structure to resist more blast load.

5.1.2 High-Explosive Field Tests

With the negotiation of the Test Ban Treaty in 1963, the Defense Atomic Support Agency, now the Defense Nuclear Agency, turned to high-explosive tests to continue the development of nuclear-resistant military structures and equipment.

An agreement was reached with the Canadian government for U.S. participation in high-explosive field tests which the Canadians had been conducting since the early 1960s. The tests were conducted at Suffield Experiment Station in southern Alberta by the Canadian Defense Research Establishment. A test in 1961 using 100 tons of TNT included experiments with 1/10th-scale concrete slabs at the surface and belowground (Purdie, 1964) and tests at 50 psi of 1/12th-scale concrete structures (Davies, 1963).

The test charge was raised to 500 tons of TNT in OPERATION SNOWBALL, the first large-scale U.S. high-explosive test (General Electric Company--TEMPO, 1965). The test was held in New Mexico in July 1964 and included experiments with buried concrete arches (Palacious and Kennedy, 1967; Sager, 1965). Kennedy (1970) also reported tests on a half-scale, flexible arch shelter in dense sand in OPERATION PRAIRIE FLAT, a 500-ton TNT shot in Canada in the summer of 1968.

OPERATION DIAL PACK, another Canadian test, followed in July 1970. DIAL PACK was a single 500-ton TNT blast. Various shelter types were included in the event: Canadian family blast shelters (Jones, Johnson, and Reid, 1972), concrete arch bunkers (McGrath, 1971), and even a fiberglass blast shelter (Nielsen, 1981).

This test was followed by the U.S. test, MIXED COMPANY, in November 1972. This was a 500-ton, TNT shot with foreign participation from several NATO countries (General Electric Co., 1973a, 1973b). The personnel shelters which were tested included a variety of wooden structures by the Waterways Experiment Station (Ball, 1974) at 15, 30, and 100 psi and also included a 1/2-scale corrugated metal arch. This test was also the first blast test of expedient shelters by the Oak Ridge National Laboratory (Kearny and Chester, 1974).

The DICE THROW event, conducted by the United States in October 1976, was a 600-ton ammonium nitrate-fuel oil (ANFO) explosion. The ammonium nitrate and fuel oil explosive, in addition to costing less than 1/10th as much as TNT, is also a clean explosive which does not cover everything with the black, greasy soot characteristic of TNT shots. Many varieties of expedient shelters were tested by the Oak Ridge National Laboratory in this event, including a Russian small-pole shelter at 53 psi (Kearny and Chester, 1978). It was found that unshored covered trenches, even in the hard desert soil at the test site, collapsed from ground motion at relatively low overpressures. Concepts like the rug-covered trench were abandoned completely. There was participation from NATO countries including tests of shelters from West Germany, Norway, and Sweden (General Electric Co., 1977a, 1977b, 1977c; Watt and Kaufmann, 1978; Watt, Kaufmann, and McVay, 1979; Watt, Zahlmann, and Cole, 1977).

MISER'S BLUFF, a 120-ton ANFO explosion, in June 1978 included tests of buried shelters up to 100 psi. The small pole shelter was tested by Oak Ridge National Laboratory (Kearny, Chester, and York, 1980) and the DONN Corporation tested a corrugated metal shelter at that overpressure (Petras et al., 1979a, 1979b). In this test, West Germany had both a basement shelter and a Swedish design modeled after the Russian small-pole shelter (Strode et al., 1979a, 1979b, 1979c). A test of a Swedish vault shelter was reported by Stephens (1979). In the MISER'S BLUFF test, the Boeing Company demonstrated on a mass scale the ability of earth arching to protect industrial equipment by covering the equipment with bags of aluminum chips and then with a few feet of soil (Strode et al., 1979b).

The MILL RACE Event in September 1981 was a 600-ton ANFO shot which saw further development of expedient hardening and crisis upgrading (Tansley and Zaccor, 1982). There were tests of a timber version of the expedient small-pole shelter, Swedish field fortifications, tests of U.S. military portable shelters, aboveground host area structures, basement structures, and keyworker shelters, as well as utility vaults used as shelters (Reid and Grayson, 1982a, 1982b, 1982c).

The DISTANT RUNNER test series included two 120-ton ANFO explosions in September and October 1981. These events were specifically intended to test aboveground, NATO-type aircraft shelters. Two such structures were subjected to 13 and 17 psi (Bousek, 1982; Flory, 1982; Rooke, 1983).

The DIRECT COURSE test in October 1983 was another 600-ton ANFO test which included further demonstrations of expedient industrial hardening and upgrading of basements (Wilton and Zaccor, 1984). The U. S. Army Corps of Engineers tested an entrance and an improved blast door for shelter for critical workers (Hyde and Kiger, 1984). A buried 1/4-scale corrugated metal shelter was tested at 200 psi; the design of this cylindrical structure offers the potential to greatly reduce fabrication costs of corrugated metal shelters. A 0.080-in-thick membrane door was tested and survived 200 psi (Zimmerman and Chester, 1984). Also tested were corrugated metal closures and high-rise basement shelters (Raska and Grayson, 1985).

The most recent high-explosive test was the MINOR SCALE event held in New Mexico in June 1985. This 4800-ton ANFO explosion simulated the airblast of an 8-kT nuclear weapon; it was the largest planned non-nuclear explosion in history. In addition to experiments on military equipment and structures, a 100-man belowground concrete box shelter was tested by the Army Corps of Engineers as part of the keyworker shelter program. Published results from MINOR SCALE are not yet available.

High-explosive tests, while not producing long duration overpressure or initial nuclear radiation, do offer very large test areas at very little cost. Quarter-scale models can be tested; they provide the response of a full-scale test object to smaller strategic nuclear weapons. However, such tests provide only very short duration overpressures. Objects buried at depths where the travel time of the shock wave in soil from the surface to the test object is comparable to the positive duration of the blast wave will not respond fully to the overpressure. The use of scale models to avoid this difficulty has its own set of problems. Where forces due to gravity are important in stresses on the test object, the object will, again, not respond fully. Reducing the scale of a model has the same effect as reducing the gravitational field on the prototype.

5.1.3 Laboratory Simulation Testing

There are other explosive techniques for simulating nuclear overpressures and durations on test items. To simulate large-yield weapon durations on buried structures, the High Explosive Simulation Technique (HEST) can be used. In this technique the structure is buried, then covered by a cavity containing explosives and a heavy earthern berm. By varying the volume of the cavity, the amount of explosive in it, and the thickness of the earth cover, any combination of weapon yield and overpressure can be simulated (Wampler et al., 1978). This technique suffers from the shortcoming that there is no negative phase of the overpressure, and there is danger of the experiment being damaged by dirt and structural material falling back into the test area.

Shock tubes can be used to apply both overpressure and dynamic (wind) pressure to experimental objects small enough to fit in the tube. Large-diameter shock tubes are in operation at the Ballistic Research Laboratories at Aberdeen Proving Ground, Maryland.

Waterways Experiment Station in Vicksburg, Mississippi, has a number of weapon overpressure simulators. These consist of vertical cylindrical tanks which can be pressurized dynamically with explosives or statically with water. Scale models can be tested in the earth-filled lower section of the tank (Flathau and Balsara, 1978; Guice and Slawson, 1986). Overpressures of several hundred psi and any duration can be obtained in these simulators.

Unlike shock tubes, these simulators do not produce a blast wind or dynamic overpressure on drag-sensitive targets.

High-explosive testing and/or simulation techniques are available which can simulate most of the blast effects of nuclear weapons. Using these techniques, designs can be tested to provide high confidence that a shelter will perform according to design in a nuclear weapons environment. The techniques do not simulate every nuclear weapon effect simultaneously; notably missing are initial nuclear radiation and ground motion of a magnitude equal to that produced by large-yield nuclear weapons. At high overpressures from small weapons, these effects largely control the design. Caution must be exercised to prevent over confidence in high pressure shelter designs simply because they have been tested in high explosive simulations.

For additional information on laboratory testing of shelters, the following references are suggested: Albritton and Balsara (1980); Allgood, White, Swalley, and Gill (1963); Bakos (1969); Criswell (1972); Gabrielsen and Wilton (1974); Leskys and Albritton (1968); Walker and Bultman (1984); Willoughby, Wilton, and Gabrielsen (1967, 1969); Wilton and Gabrielsen (1972, 1973); Woodson (1984).

5.2 HABITABILITY TESTING

Habitability testing of actual shelters has been done for three reasons: (1) to conduct engineering evaluations of the shelter and its various systems, (2) to conduct psychological evaluations of shelter occupants and shelter managers during actual in-shelter tests, and (3) to provide information on adequate ventilation rates inside shelters. The first two categories have involved actual, long-term (up to two weeks) occupancy experiments. The third category of tests has largely been done in unoccupied shelters. Wright, Chessin, Laney, and Cox (1982) have attempted to summarize the findings of these shelter habitability studies. A more detailed description of such experiments is given in this section.

5.2.1 Engineering Aspects of Habitability

Shelter occupancy experiments began in 1959 (Vernon, 1959), when Princeton University made the first attempt to determine whether or not a family could remain confined in a shelter for a period of 14 days and to determine the nature and gravity of any problems associated with shelter occupancy. The five-member family remained in an 8-ft by 9-ft basement fallout shelter for the first two weeks of August 1959. The shelter was stocked with food, water, a manual blower, and a chemical toilet. Although the temperature inside the shelter reached 79°F, the family was able to remain comfortable by operating the blower for approximately five minutes every half hour during the period when they were awake. The study was successful in that it clearly indicated that this particular family was capable of easily withstanding the full 14 days of shelter confinement; no major problems developed.

Altman, Smith, Meyers, McKenna, and Bryson (1961) of the American Institutes for Research (AIR) followed several, brief pilot studies with a set of four experiments, each with a 30-person group occupying a simulated shelter. Three of these occupancy tests were each run for a duration of one week; the fourth lasted two weeks. The major experimental variables were the shelter temperature and the presence or absence of a trained shelter manager. The shelter occupants were paid volunteers of both sexes, ranging in age from 7 to 72. The simulated shelter was approximately 12 by 20 ft with an actual floor area of 242 ft^2 (8 ft^2 for each occupant).

The AIR tests measured the tolerance of shelter occupants to increases in the "effective temperature" of the shelter. The "effective temperature" is that temperature of air at 100% relative humidity which causes the same sensation of warmth or cold to the human body as does the existing room temperature and humidity level. In one of the AIR tests, the effective temperature climbed to 85^oF, a level which the investigators found to be tolerable but near the threshold of intolerance. At this temperature, the shelter occupants exhibited profuse perspiration, reduction of activity, lack of concentration, headaches, nausea, and elevated body temperatures. The investigators found that "personal effectiveness and shelter organization would be seriously impaired by higher temperatures for a prolonged period."

During the last 20 hours of the two-week AIR test, eleven additional occupants were admitted to the shelter in order to simulate overcrowding. The 30 bunks, which could be disassembled for increased daytime floor space, provided adequate sleeping space for all of the additional shelter occupants. Even with this increased number of occupants (41 total occupants at 6 ft^2 per person), no major problems or conflicts developed.

The U.S. Navy conducted several shelter occupancy tests between 1959 and 1963. Each of these was an "engineering evaluation" of shelter equipment and procedures. Two shelters were used: one in Camp Parks, California, and the other in Bethesda, Maryland. The shelter design used in these tests was the same as the buried, corrugated-metal, steel arch which had been tested in the OPERATION PLUMBBOB nuclear test series of 1957 (Albright, Beck, LeDoux, and Mitchell, 1961). The 25-ft by 48-ft shelters were designed for occupancy by 100 persons at 12 ft^2 per person. The shelters were equipped with plumbing for the drinking water and for the toilets and also with an electric generator system for powering the lighting system and the ventilation blower.

Four tests were conducted by the U.S. Naval Radiological Defense Laboratory (USNRDL) using the Camp Parks shelter. In October 1959, 100 male volunteers (inmates from a minimum security prison) occupied the shelter for two weeks (Goldbeck and Newman, 1960). The shelter temperature ranged from 71 to 81°F. A diurnal variation of temperature was observed inside the shelter; the ventilation blower had to be shut off at night to retain warmth in the shelter. Because only 50 of the occupants could be seated at one time, insufficient seating space was a major problem. In December 1959, the second Camp Parks test also used 100 male inmates as shelter occupants (Strope, Etter, Goldbeck, Hieskell, and Sheard, 1960). No problems were observed during this two-week trial; the mean effective shelter temperature was about 70°F.

In the USNRDL test of July 1960, 100 men occupied the shelter for 100 hours (Strope et. al, 1960). The outdoor temperature reached a maximum of 93°F, but the shelter never exceeded an effective temperature of 81°F. Average daily water consumption was about 3 quarts per person. The investigators reported that the high temperatures seemed to have no effect on the activity of the occupants during this short-duration test. A set of low-cost, fiberboard furniture was included in the test; the resulting wear on this furniture provided insights into better designs (Norman Steuer Associates, 1963).

In the fourth and last Camp Parks test, a mix of men, women, and children occupied the shelter (Strope, Etter, Schultze, and Pond, 1962). These 99 occupants were approximately 50% male and 50% female, with each of these groups further subdivided into 50% adult and 50% children. The largest family unit was seven persons. Ages ranged from 3 months to 68 years. They occupied the shelter for 48 hours in November 1960. The short duration of this test was determined from the observation that, in earlier tests, most shelter problems developed within 48 to 72 hours after the shelter was occupied. Outdoor temperatures ranged between 40 and 63°F, while the effective temperature inside the shelter varied from 66 to 76°F. Average daily water consumption was 2.5 quarts per occupant. Problems with the bunk design were encountered, and a new design was developed.

The conclusions drawn from the USNRDL Camp Parks experiments were that the capacity of the shelter could be increased by up to 100% without imposing serious hardships for the shelter occupants. With 200 occupants inside such a shelter, the floor space per occupant would become 6 ft^2. Restricted use of water was the number one complaint in these tests; lack of space (crowding) and excessive noise were the next two areas of discomfort.

During 1962, the Navy conducted both winter trials (Ramskill et al., 1962) and summer trials (Bogardus, 1968) in the Bethesda, Maryland, shelter. Each occupancy test lasted for two weeks and involved 100 male Navy volunteers who had been psychologically and physically screened for these tests. Only 50 bunks were provided for the 100 men; sleeping was accomplished in shifts.

The Navy winter trials were conducted in February 1962. Despite the fact that outdoor temperatures were in the range of 12 to 55°F and that the shelter had no artificial heating, the temperature inside the shelter was maintained at 70 to 80°F by adjusting the flow rate of the blower. The blower used in this test had a capacity of 600 cubic feet per minute. The average daily water consumption of each shelter occupant was slightly less than 2 quarts per day. No major problems developed during this test.

For the Navy summer trials in August 1962, the blower capacity was increased to 1200 cubic feet per minute due to anticipated problems with cooling the shelter. This still did not alleviate the problems associated with an 85°F effective temperature during the first week and 80°F during the second week. The average daily water consumption of the shelter occupants was 3 quarts per day. The investigators concluded that it was highly improbable that the shelter occupants could have survived a second week with an 85°F effective temperature; the men's bodies were constantly wet from perspiration. This constant wetness also applied to the men's bunks which never dried out during the duration of the test. The rough canvas of the wet bunks aggravated the heat rash and other medical problems developed by the occupants. One shelter occupant failed to complete the test due to heat-related problems; the attendant medical officer handled similar problems for five other occupants.

The last of the Navy occupancy tests occurred in May 1963 (Ross, Trumbull, and Williams, 1965). The unique character of this test was that it was conducted as an impromptu exercise; previous occupancy experiments had used volunteers who had been carefully screened before each test. The 1963 Navy test included Navy officers who were involved in continuing education seminars at the Naval Medical Center. Thirty-four men were taken on a tour of the same shelter used in the 1962 Navy summer and winter trials (described above). At that time, it was announced that these men were to be voluntarily confined for an unknown duration under simulated emergency conditions as part of a shelter occupancy experiment. The men were given the chance to refuse to participate; however, all 34 remained in the shelter. The simulation lasted four and one-half days. The outdoor air temperature remained between 5 and 10°F, but the shelter temperature was 60 to 70°F; many of the shelter occupants complained of discomfort from the cold. The concrete floor of the shelter remained very damp for the duration of their stay. No major problems developed during this short test.

The Navy tests identified several areas of shelter living which required minor adjustment on the part of the shelter occupants. Psychologically, the most discomfort during the occupancy tests was caused by lack of water for washing (hygiene), temperature and humidity, lack of privacy (crowding), and noise.

All of the above tests were conducted inside existing shelters, many of which had modern plumbing connections, electric power, and operating toilets. The only extremely austere occupancy tests of shelters were conducted by the Oak Ridge National Laboratory (Kearny, 1976, 1979) as part of the expedient shelter study. Families were given instructions on how to build and equip an expedient shelter (See Section 7.3); they were paid for their labor, and in addition, they received a bonus payment if they actually spent the night inside their shelter. The longest period of occupancy was recorded for a family of six who constructed a 3.5-ft-wide by 4.5-ft-high by 16.5-ft-long, log-covered trench shelter and then occupied it continuously for 77 hours (a four-night stay). Although the family had only a limited food and water supply, a chemical toilet, and no electric power, they experienced no occupancy problems.

5.2.2 Psychological Aspects of Habitability

The two most significant and extensive studies on the psychological aspects of shelter occupancy were conducted by Collins and Bend (1966, 1968) and by the University of Georgia (Hammes, 1963a, 1963b, 1964, 1965; Hammes and Ahearn, 1966, 1967; Hammes, Ahearn, and Foughner, 1968). Collins and Bend conducted a mail survey of people who had participated in shelter occupancy exercises as part of a shelter management training course which they took through the Civil Defense University Extension Program. This program involved 50 different colleges throughout the country; 60 instructors and 1320 students responded to the survey. The size of each group of shelter occupants ranged from 16 to 30 people; their ages ranged from 20 to 50. Only a few of these occupancy experiments lasted for more than one day; however, more than one-third were overnight stays. Almost all of the tests were conducted in Federally marked fallout shelters. Among other findings, the survey responses indicated that five major factors affected shelter living the most: the inability to sleep, the lack of privacy, the lack of physical activity or exercise, the temperature and humidity inside the shelter, and the unavailability of seating space (overcrowding).

The University of Georgia studies are significant, not only for the large number of total participants, but also for an orchestrated effort to duplicate the U.S. census population statistics (sex, race, age, etc.) among the shelter occupants. Twelve community shelter occupancy experiments were conducted between 1962 and 1967. Hammes, Ahearn, and Foughner (1968) summarize the findings. The size of the shelter groups ranged from 30 to over 10; the ages were from 6 months to 79 years. The longest tests lasted two weeks; the shortest were weekend stays. Both winter and summer tests were included. In two of the tests the available shelter floor space was 6 ft^2 per person; the floor space never exceeded 10 ft^2 per person.

Over 3500 people participated in the twelve University of Georgia tests. These people were paid volunteers, but one remarkable finding of the experiments was the rather large number of participants who elected not to stay in the shelter for the duration of the test. About 10% (344 persons) of the 3510 total shelter occupants did not complete the tests; the investigators called these people "defectors." Unbearable hot humid conditions inside the shelter provided the motivation for several of these defectors, particularly for the 20% (62 people) who left a June 1965 test which involved some 300 occupants. The highest defection rate, 40% occurred in a July 1963 test involving thirty, preteen school children. Shelterees who did endure the confinement period listed lack of water for washing (hygiene) as the primary discomfort. Other major complaints were difficulty with sleeping, temperature, inadequate sanitation facilities (toilets), and lack of space. Tolerance for continued confinement ranged, in terms of median data, from two to seven days.

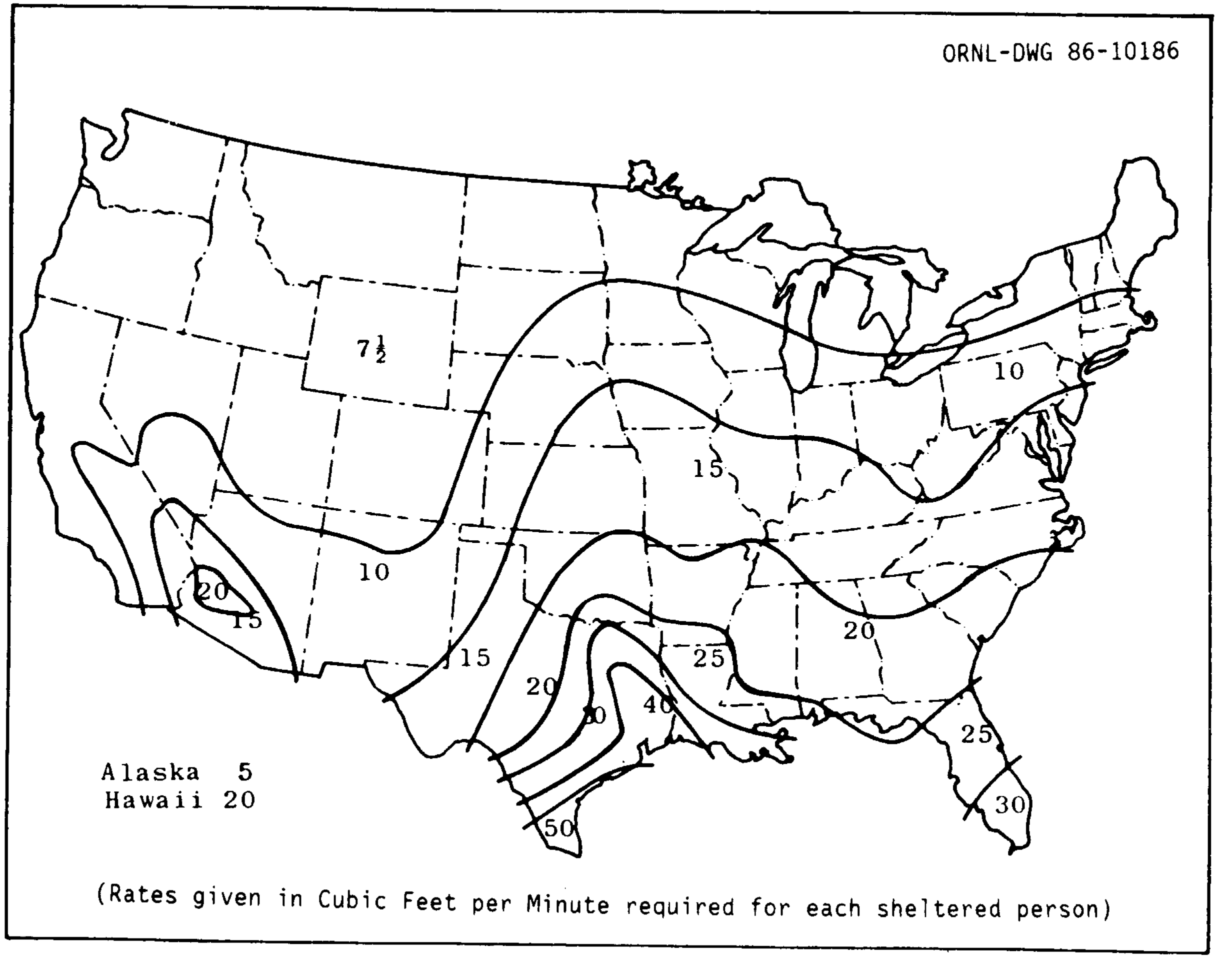
5.2.3 Ventilation Tests

One of the obvious conclusions from the above set of shelter occupancy experiments is the intolerance of shelterees to hot, humid conditions. For shelters containing more than a few people, the heat and moisture given off by each occupant becomes an important consideration with respect to keeping those occupants cool. In warm weather the temperature and humidity in the shelter can reach levels causing heat prostration and even death. In recognition of this fact, a great deal of research has been conducted to determine the ventilation requirements in both aboveground and belowground shelters (Baschiere and Lokmanhekim, 1964; Baschiere, Lokmanhekim, and Moy, 1964; Behls, Libovicz, and Engholm, April 1964, September 1964; Behls and Madson, 1965; Flanigan, Morrison, and Bass, 1966; Goldsmith, 1965; Libovicz, Madson, Behls, and Engholm, 1964; Libovicz, Van Schoyck, and Engholm, 1963; Madson, Baschiere, Behls, and Engholm, 1964; Madson, Behls, and Engholm, 1964; Madson, Libovicz, Behls, and Engholm, 1964). Most of these tests involved the use of simulated shelter occupants; these were mannequins which produced heat and humidity resembling that of a human being.

Studies were conducted on large, aboveground buildings suitable for fallout shelter by Guy B. Panero, Inc. (1965) in the New York City area and by Henniger and Madson (1966) and Poruk, Libovicz, and Engholm (1963) in the Chicago area. The investigators found that when cross-ventilation was available through open windows, natural air circulation was adequate to maintain habitable conditions most of the time in either summer or winter. In very large shelters, very little heat was lost by radiation or conduction to the walls of the shelter; the air ventilation provided the only mechanism for cooling (Combe, Nelson, and Tomcala, 1966).

Results of the other studies indicated that belowgrade shelters or shelters in the interiors of buildings without access to windows required forced ventilation at rates which depended upon the outdoor temperature and humidity; the higher the outdoor effective temperature (see Section 5.2.1 for a definition of effective temperature), the more ventilation was required. In warm weather, more than 3 cubic feet of air per minute must be supplied for each person sheltered, and in very hot weather, substantially more than 3 cubic feet per minute must be provided for each person.

Baschiere and Lokmanhekim (1964) calculated the summertime, forced ventilation requirements for different parts of the country. Their computations were based on meteorological data and the desire to limit the effective temperature inside the shelter to 82° (an effective temperature of 85°F had been shown to be the threshold of intolerance from previous shelter occupancy tests, see Section 5.2.1). The Defense Civil Preparedness Agency (May 1978), using modern meteorological data, has recalculated these ventilation rates for use in shelter design. Figure 5.1 is the result. It should be noted that very high ventilation rates are required in the hot, humid regions of the United States, such as along the Texas Gulf coast.



(Rates given in Cubic Feet per Minute required for each sheltered person)

Fig. 5.1. Forced ventilation requirements for U.S. shelter locations.

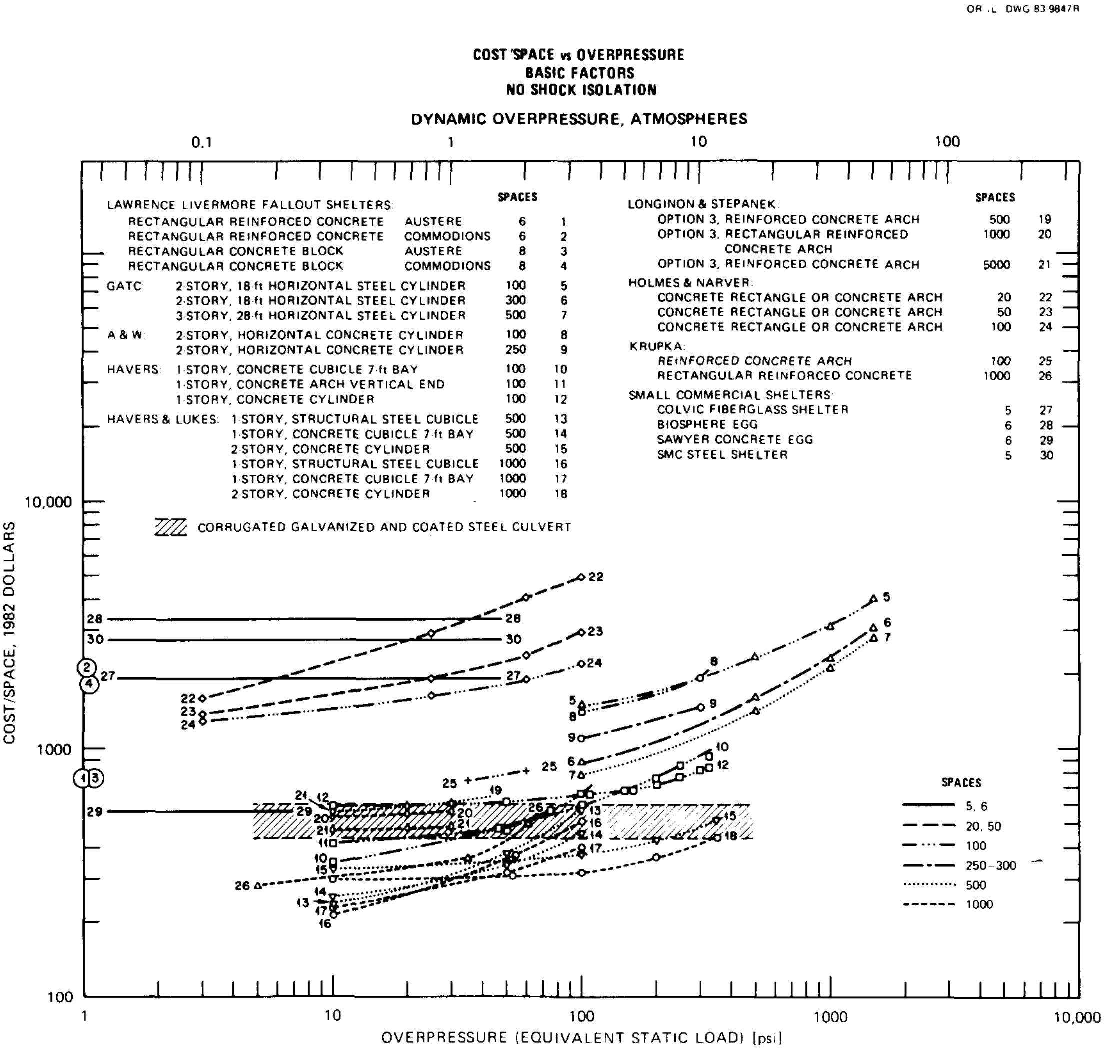


Fig. 6.1. A comparison of the most economical shelters from various design studies (cost vs overpressure protection).

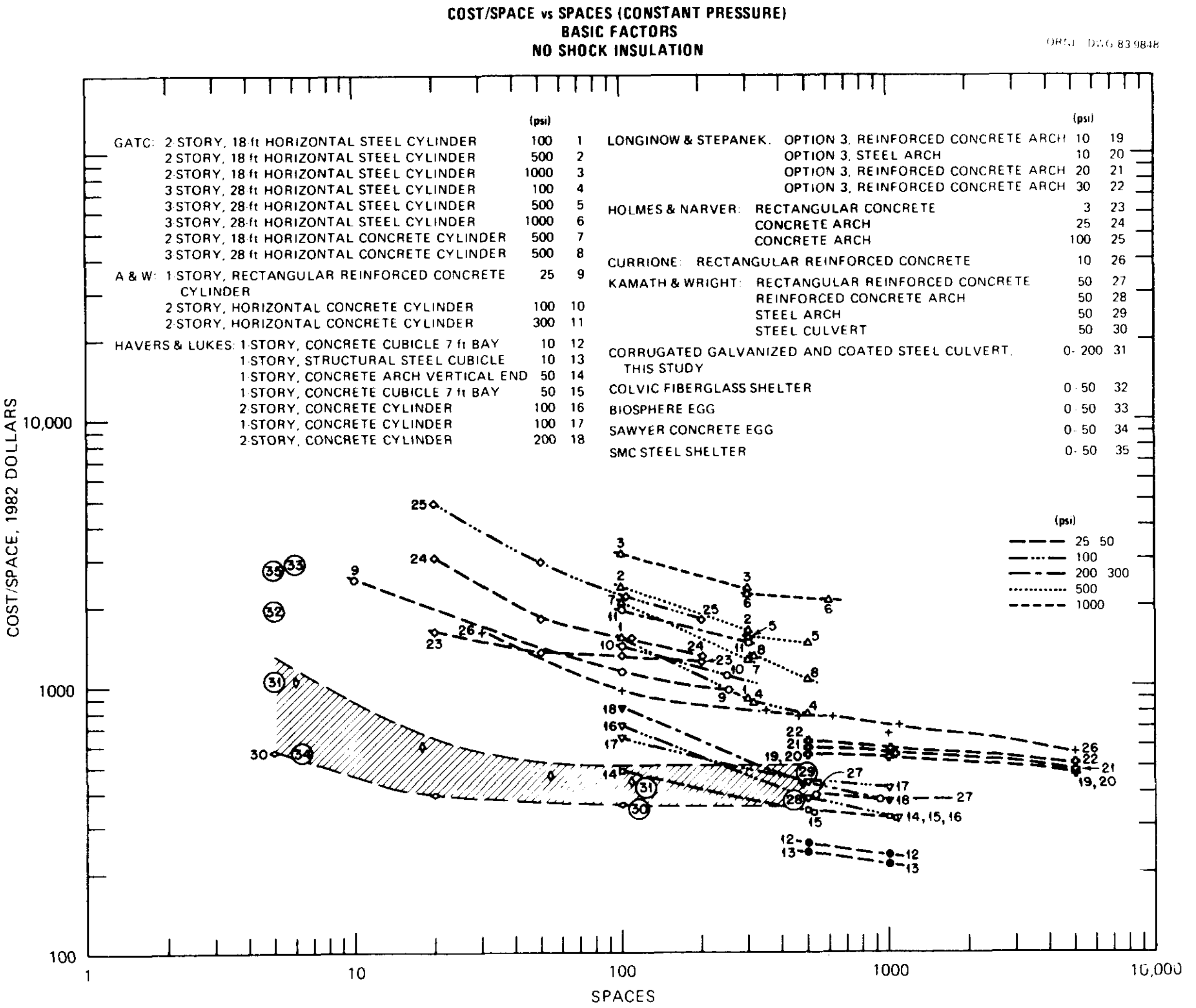


Fig. 6.2. A comparison of the most economical shelters from various design studies (cost vs shelter size).

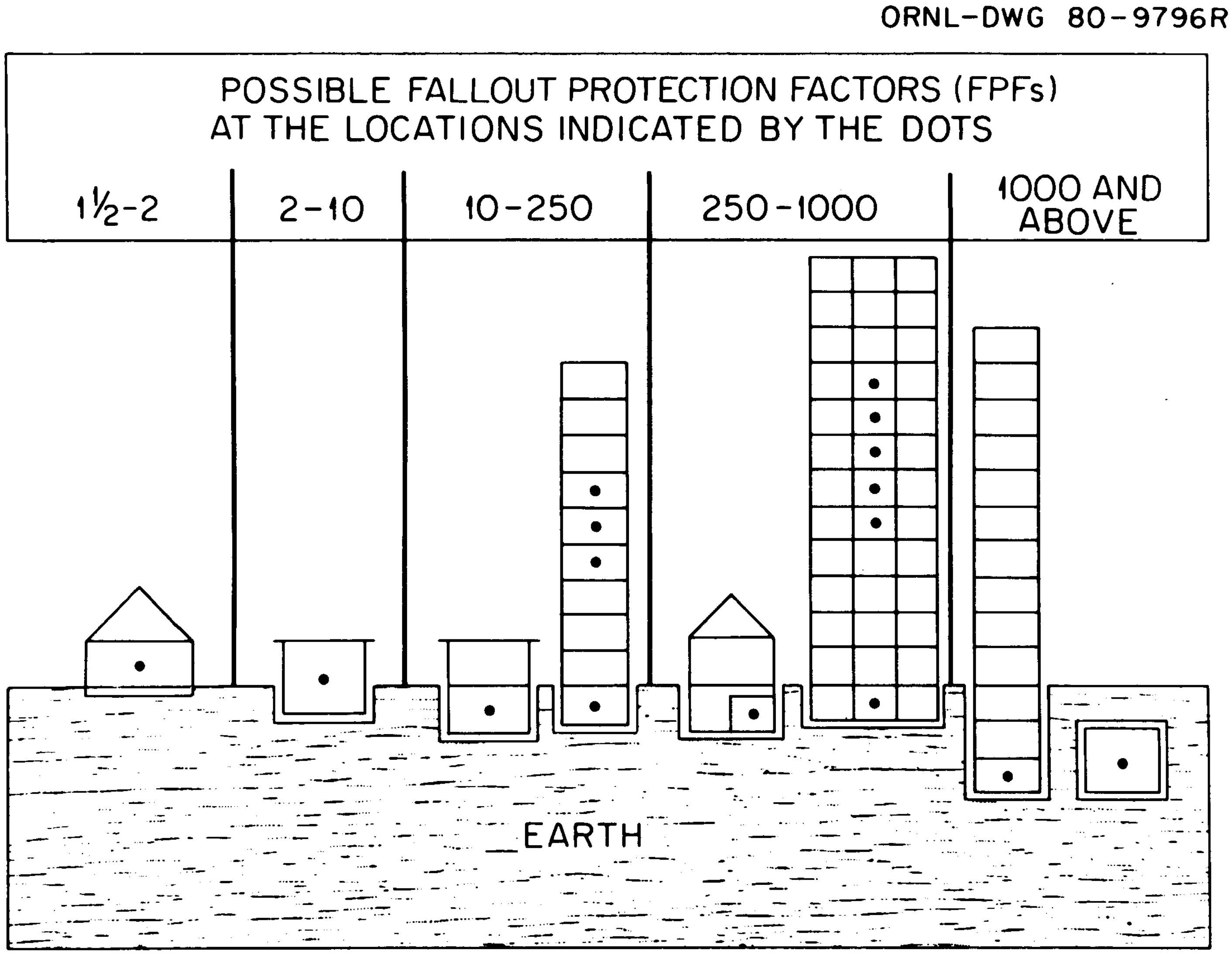


Fig. 7.1. Fallout protection available in various structures.

Table 7.1. Fallout protection factor distribution of U.S. National Fallout Shelter Space (NFSS) inventory (as of June 30, 1985)[a]

Class	Protection factor	Number of spaces
0	10-19	81,108,351
1	20-30	69,338,266
2+3	40-99	136,514,694
4	> 100	109,274,300
2+3+4	> 40	245,788,994

[a] Personal communication, Ms. Marion Rothenbuhler, Shelter Data Branch, Federal Emergency Management Agency, Olney, MD, November 25, 1985.

Table 7.2. Basement overhead (1st) floor system categories

Type of floor system	Percent of total U.S. spaces,[a] %	Mean lethal overpressure,[b] psi
Concrete slab - steel beam	22.1	12
Flat slab	4.9	8
Flat plate	5.7	7
Concrete slab - concrete beam	16.9	
Concrete joist - concrete beam	0.8	7
Concrete joist - steel beam	2.1	10
Other - Concrete slab - concrete joist Concrete slab - steel joist Concrete slab - steel/concrete beam Hollor concrete slab	20.3	7.5
Total Sample	72.8	

[a] Estimate based on 219 buildings sampled (Tolman, Lyday, and Hill, 1973). These numbers must be multiplied by 35.6% to get percentages of this type of construction located in basements. Of all spaces, 9.4% are located in basements and subbasements with no exterior wall exposed. (Longinow, 1979)

[b] Defined as that blast overpressure which will statistically produce fatalities in 50% of those exposed to the blast wave.

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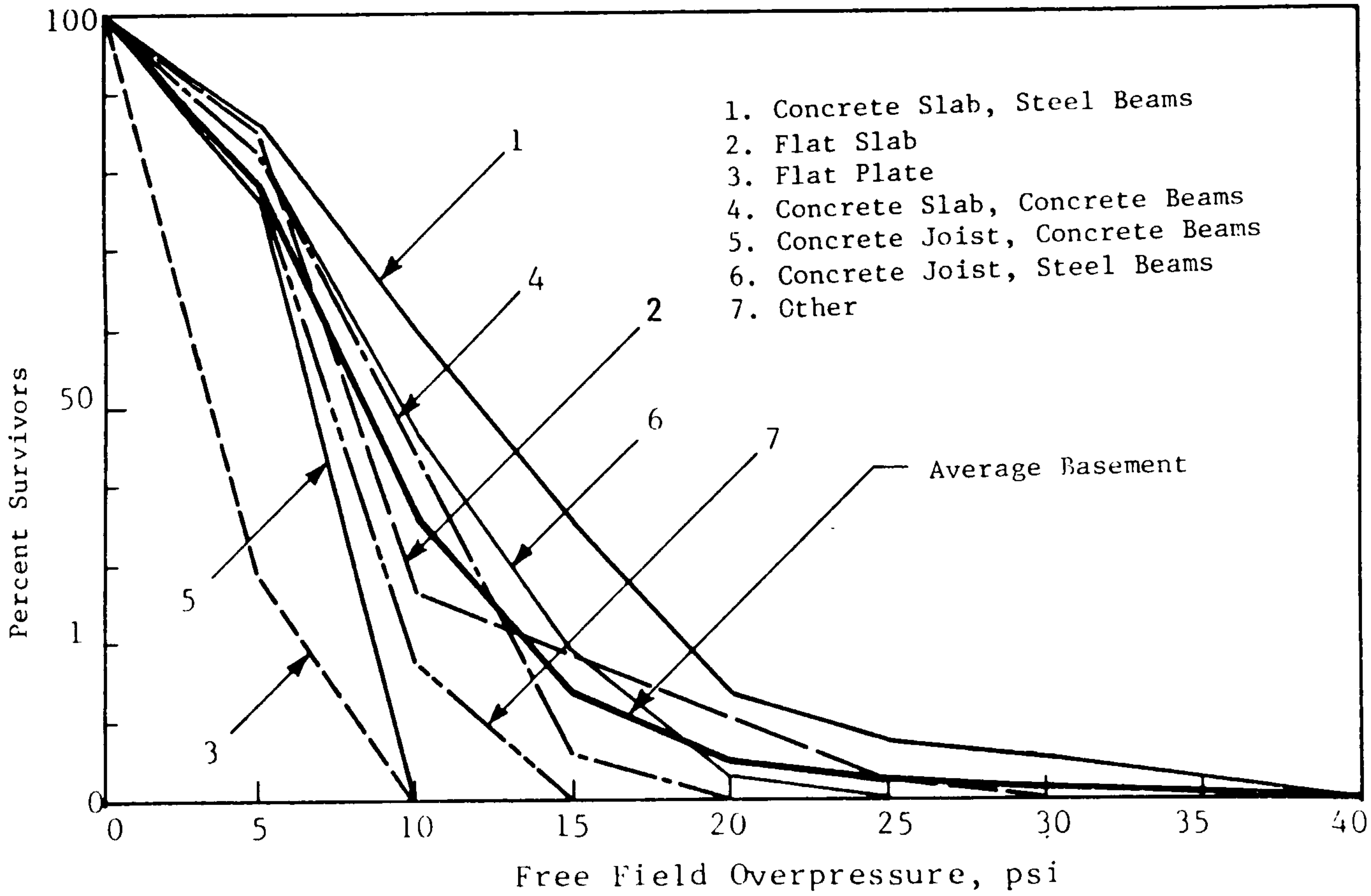

Fig. 7.2. Survival probability in basements.

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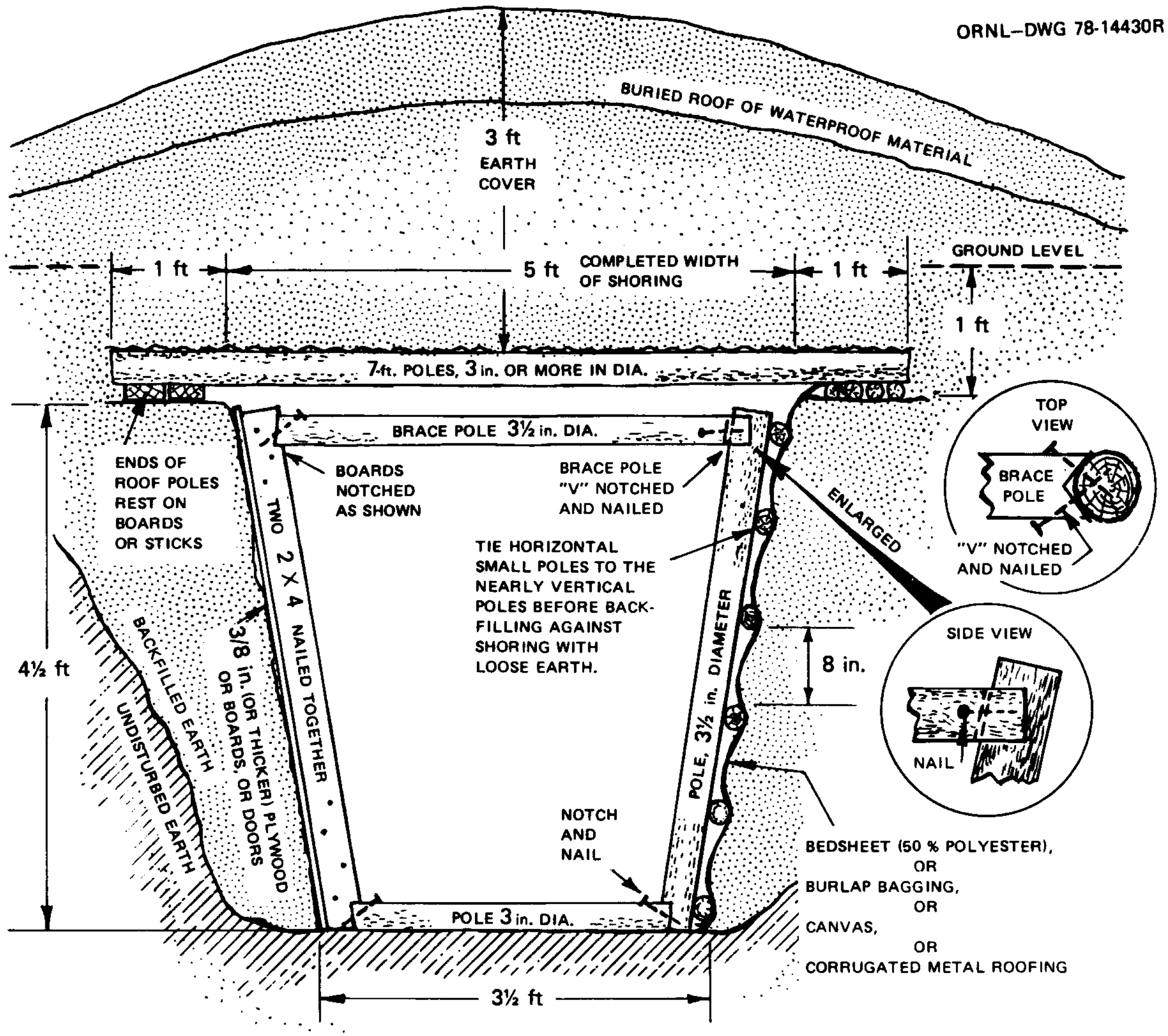
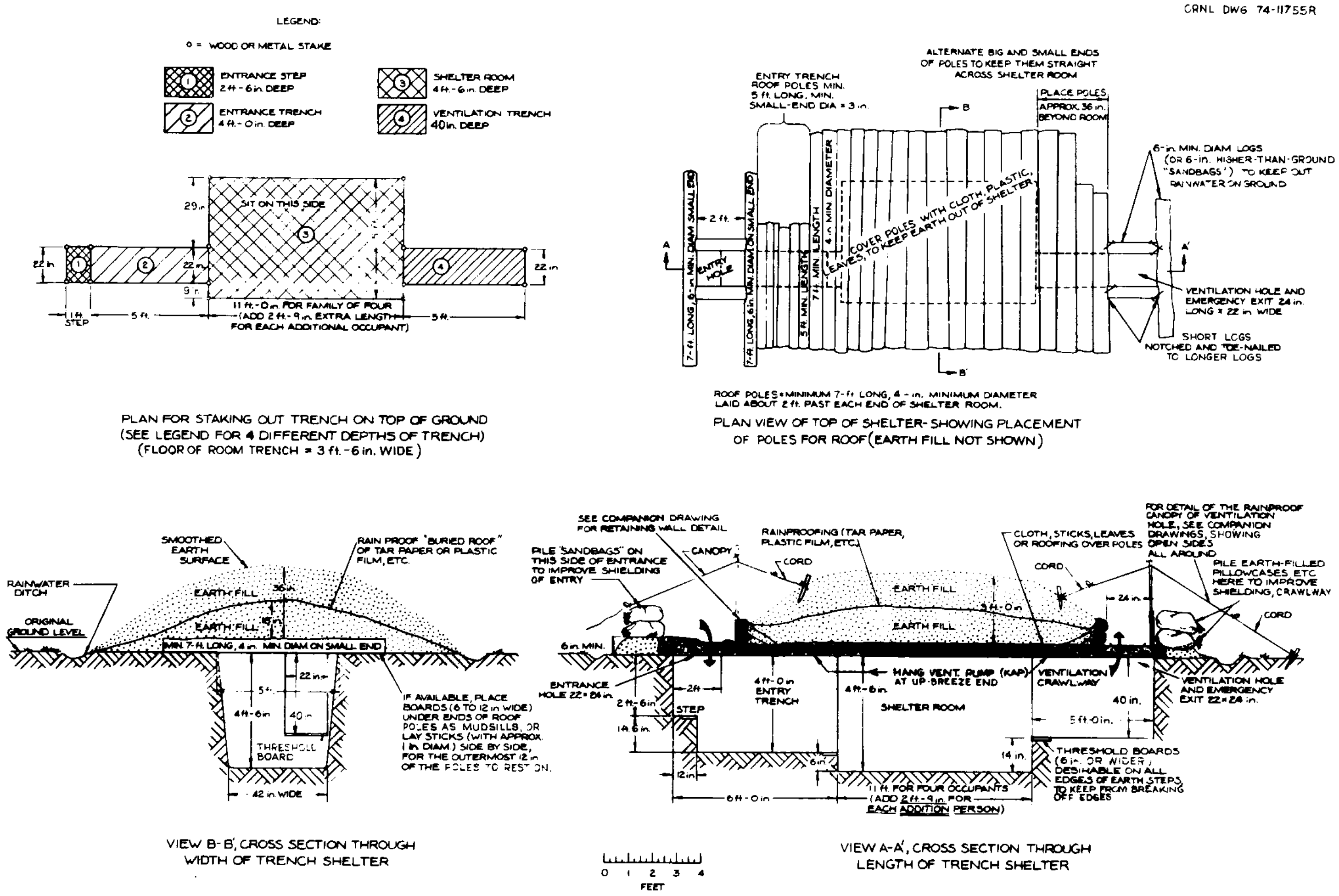


Fig. 7.3. Methods for shoring a trench shelter.



PLAN FOR STAKING OUT TRENCH ON TOP OF GROUND
(SEE LEGEND FOR 4 DIFFERENT DEPTHS OF TRENCH)
(FLOOR OF ROOM TRENCH = 3 ft. - 6 in. WIDE)

PLAN VIEW OF TOP OF SHELTER- SHOWING PLACEMENT OF POLES FOR ROOF (EARTH FILL NOT SHOWN)

VIEW B-B', CROSS SECTION THROUGH WIDTH OF TRENCH SHELTER

VIEW A-A', CROSS SECTION THROUGH LENGTH OF TRENCH SHELTER

Fig. 7.4a. Pole-covered trench shelter.

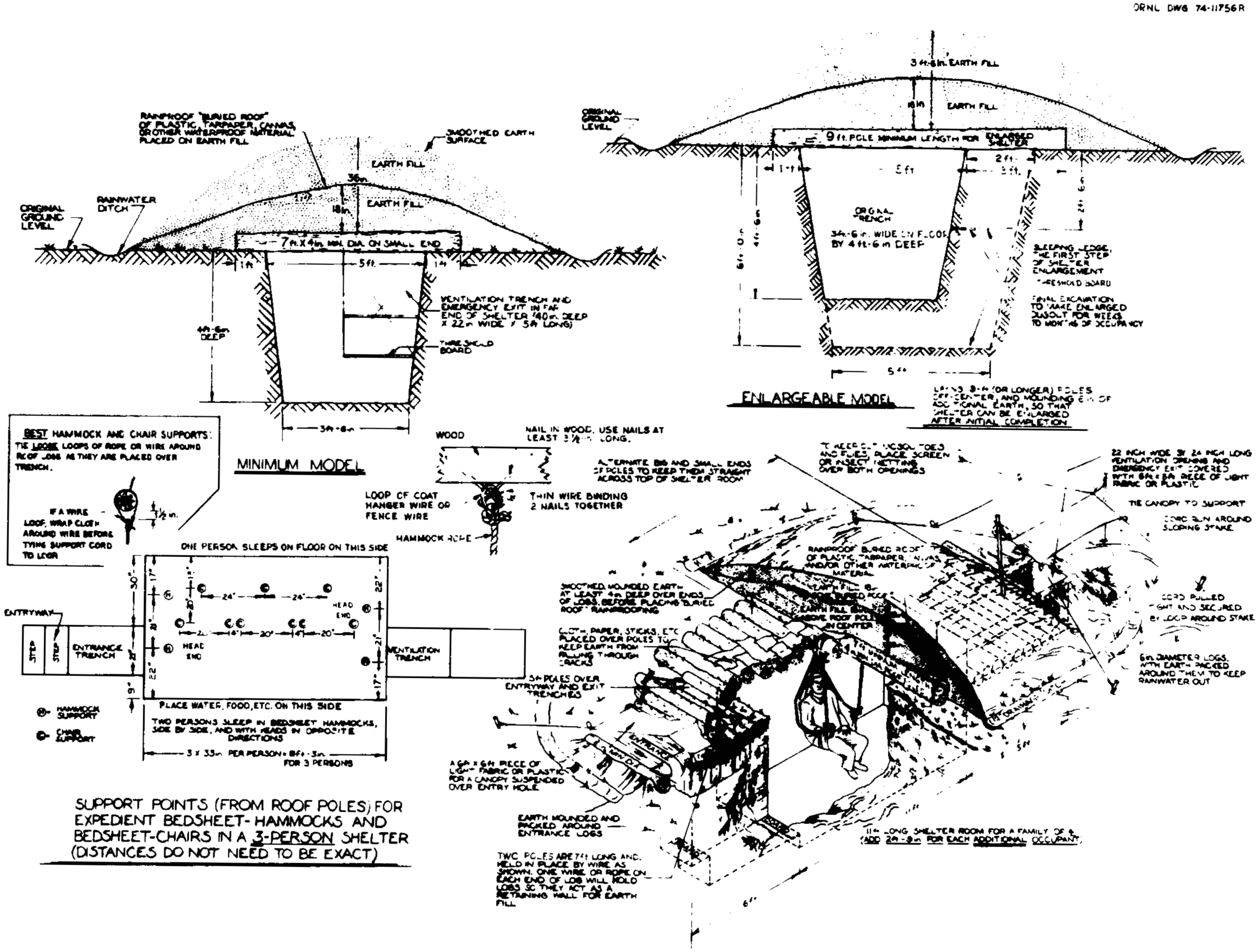


Fig. 7.4b. Pole-covered trench shelter.

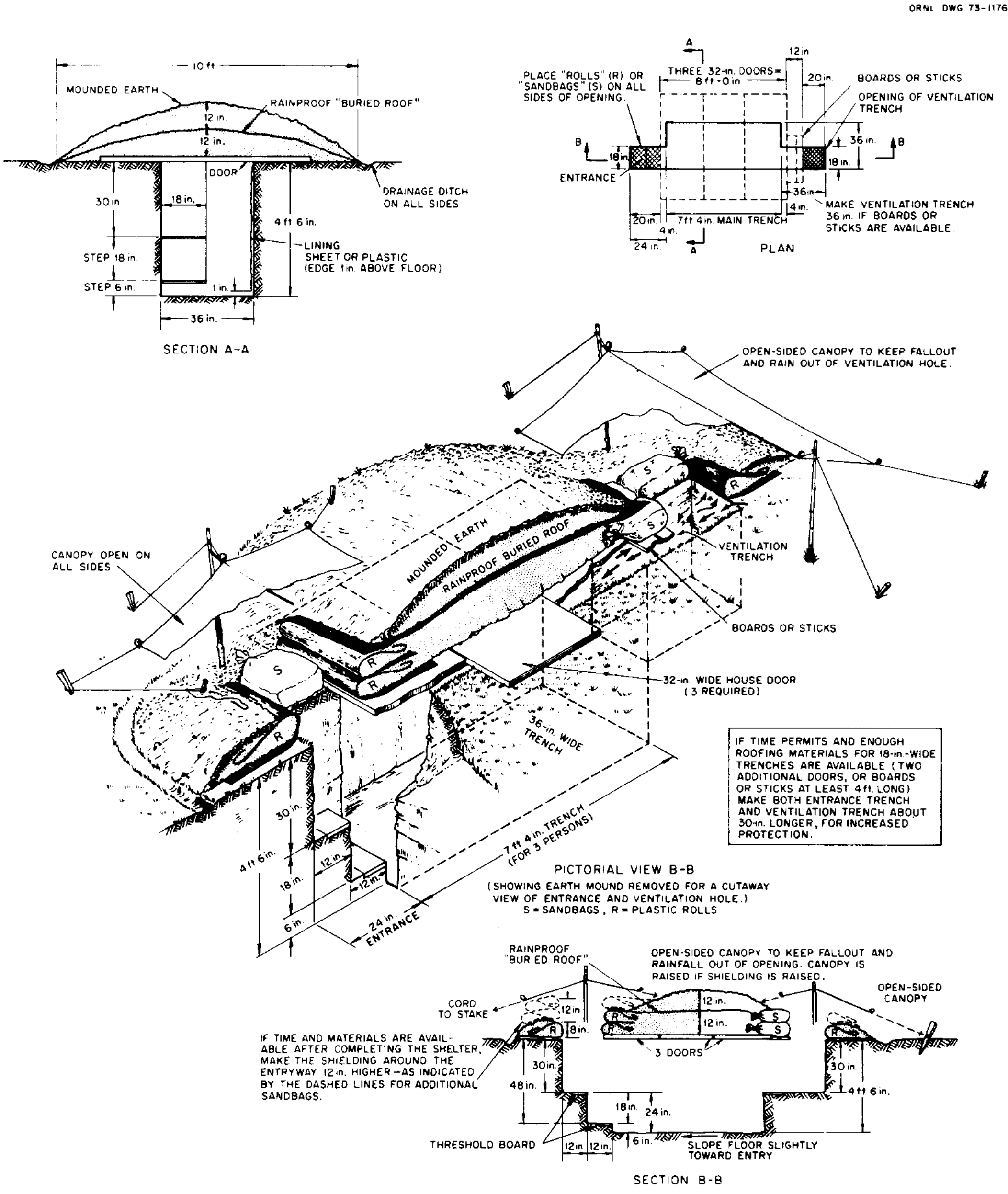
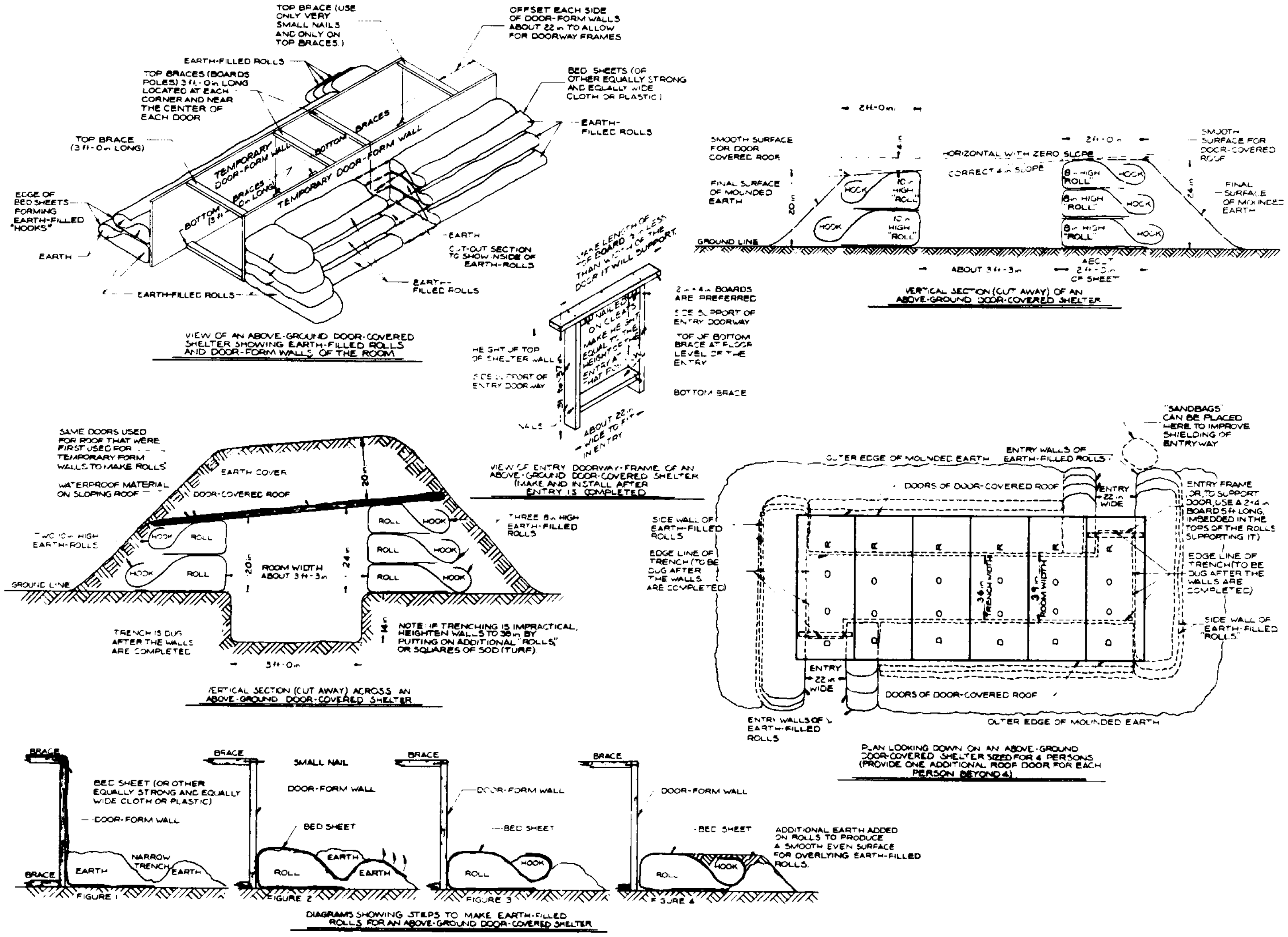


Fig. 7.5. Door-covered trench shelter.



VIEW OF AN ABOVE-GROUND DOOR-COVERED SHELTER SHOWING EARTH-FILLED ROLLS AND DOOR-FORM WALLS OF THE ROOM

VERTICAL SECTION (CUT AWAY) OF AN ABOVE-GROUND DOOR-COVERED SHELTER

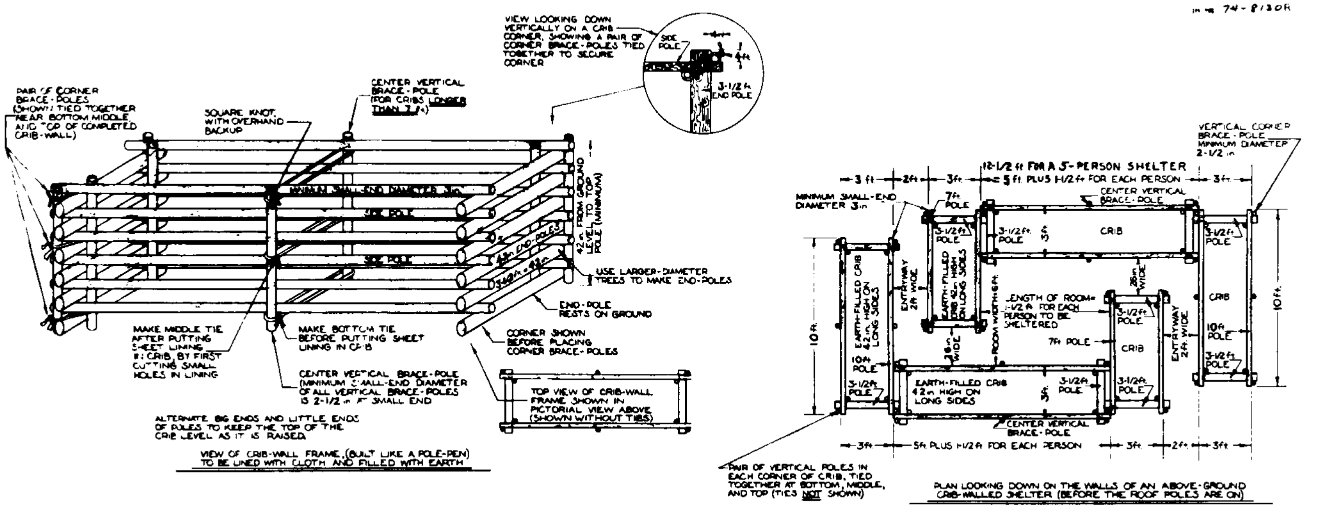
VIEW OF ENTRY DOORWAY-FRAME OF AN ABOVE-GROUND DOOR-COVERED SHELTER (MAKE AND INSTALL AFTER ENTRY IS COMPLETED)

VERTICAL SECTION (CUT AWAY) ACROSS AN ABOVE-GROUND DOOR-COVERED SHELTER

PLAN LOOKING DOWN ON AN ABOVE-GROUND DOOR-COVERED SHELTER SIZED FOR 4 PERSONS (PROVIDE ONE ADDITIONAL ROOF DOOR FOR EACH PERSON BEYOND 4)

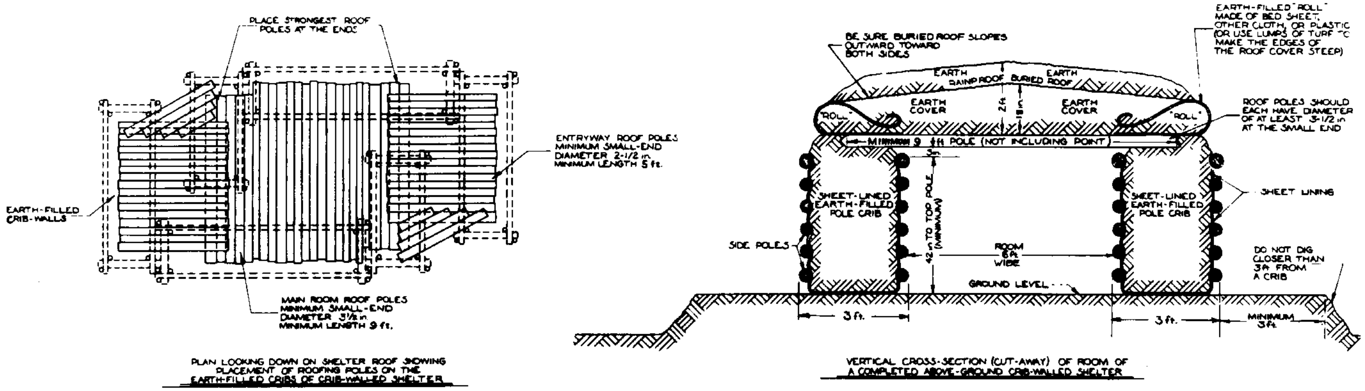
DIAGRAMS SHOWING STEPS TO MAKE EARTH-FILLED ROLLS FOR AN ABOVE-GROUND DOOR-COVERED SHELTER

Fig. 7.6. Aboveground door-covered earth roll shelter.



VIEW OF CRIB-WALL FRAME, (BUILT LIKE A POLE-PEN) TO BE LINED WITH CLOTH AND FILLED WITH EARTH

PLAN LOOKING DOWN ON THE WALLS OF AN ABOVE-GROUND CRIB-WALLED SHELTER (BEFORE THE ROOF POLES ARE ON)



PLAN LOOKING DOWN ON SHELTER ROOF SHOWING PLACEMENT OF ROOFING POLES ON THE EARTH-FILLED CRIBS OF CRIB-WALLED SHELTER

VERTICAL CROSS-SECTION (CUT-AWAY) OF ROOM OF A COMPLETED ABOVE-GROUND CRIB-WALLED SHELTER

Fig. 7.7. Aboveground Crib-walled shelter.

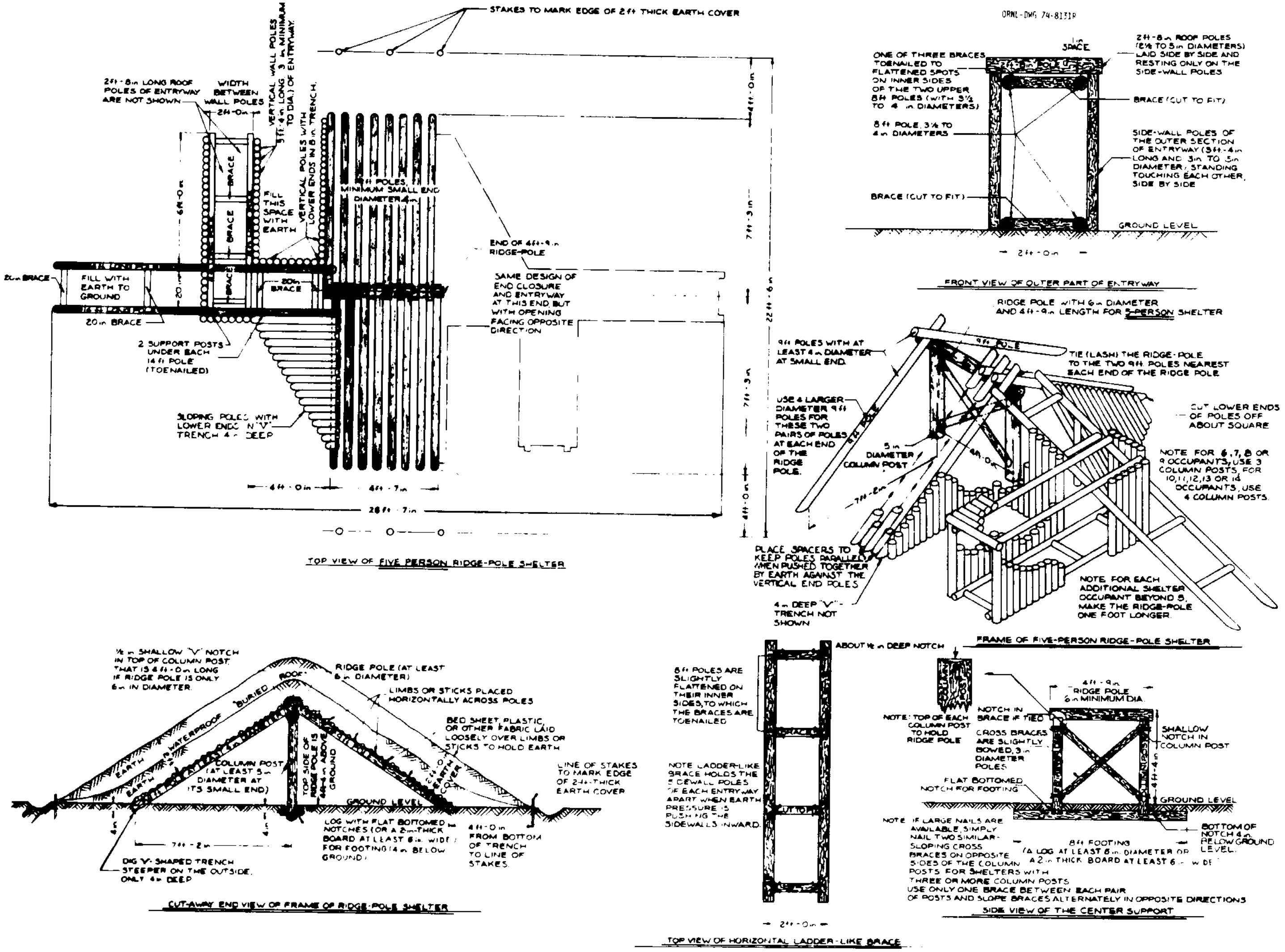


Fig. 7.8. Ridge-pole shelter.

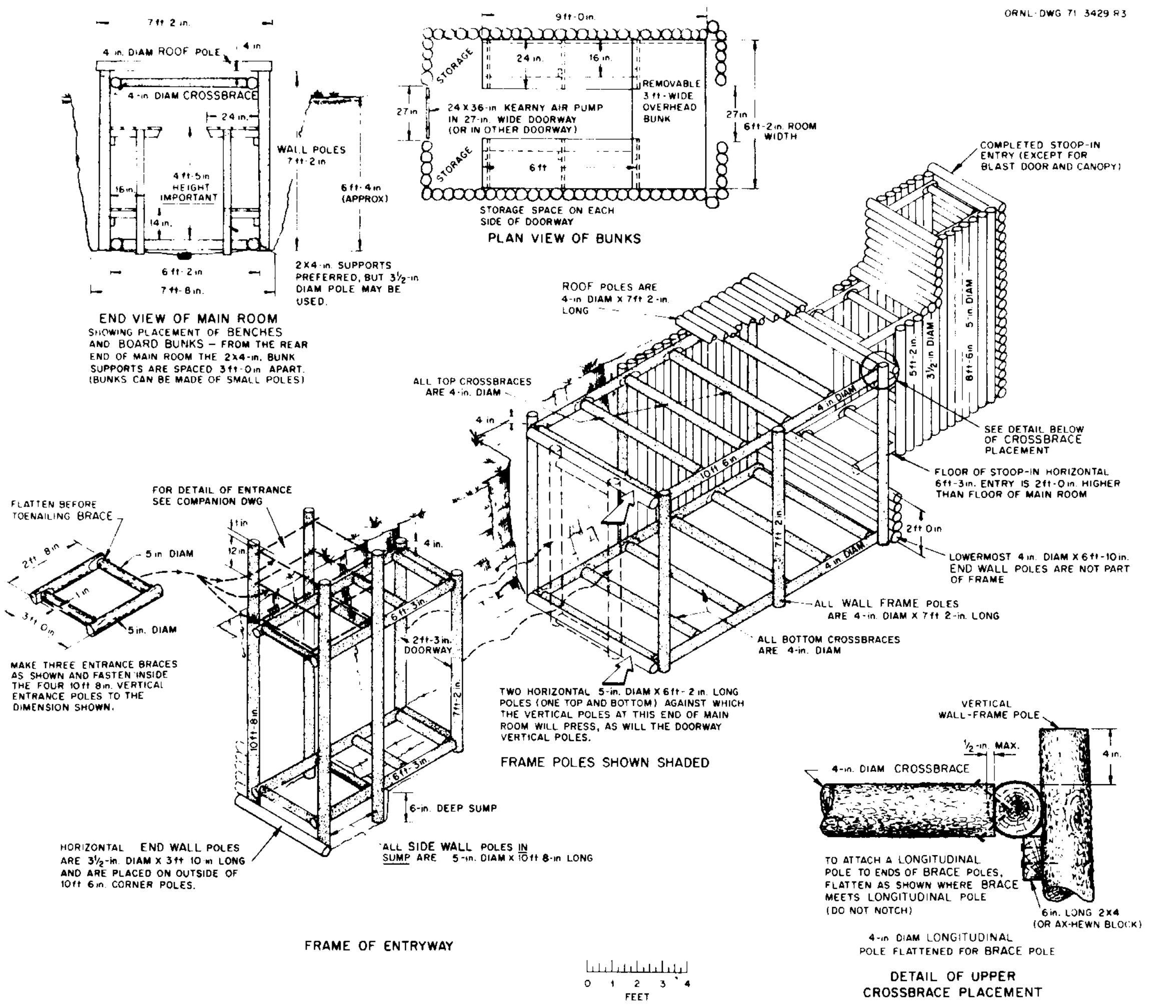


Fig. 7.9a. Small-pole shelter.

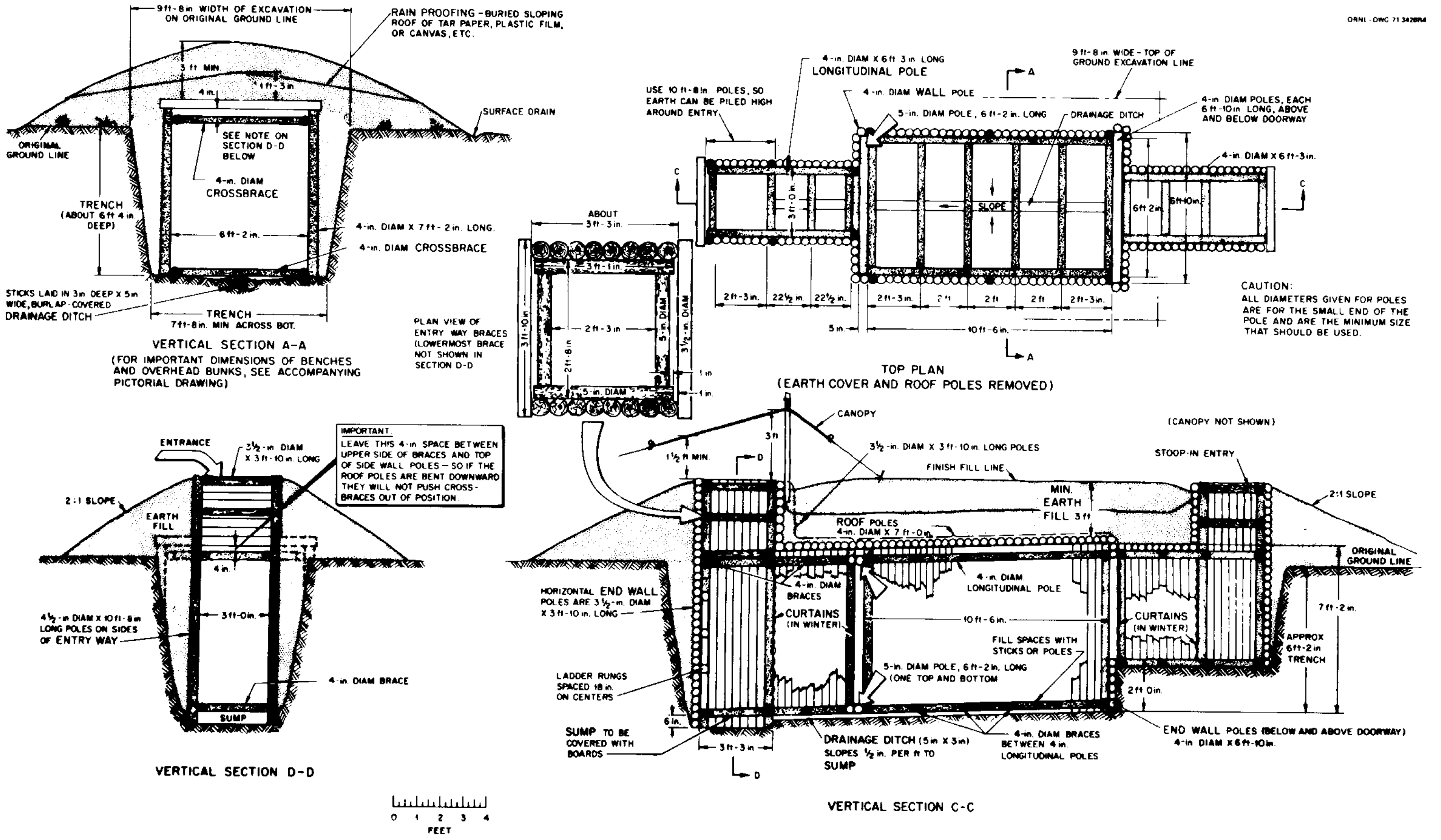


Fig. 7.9b. Small-pole shelter.

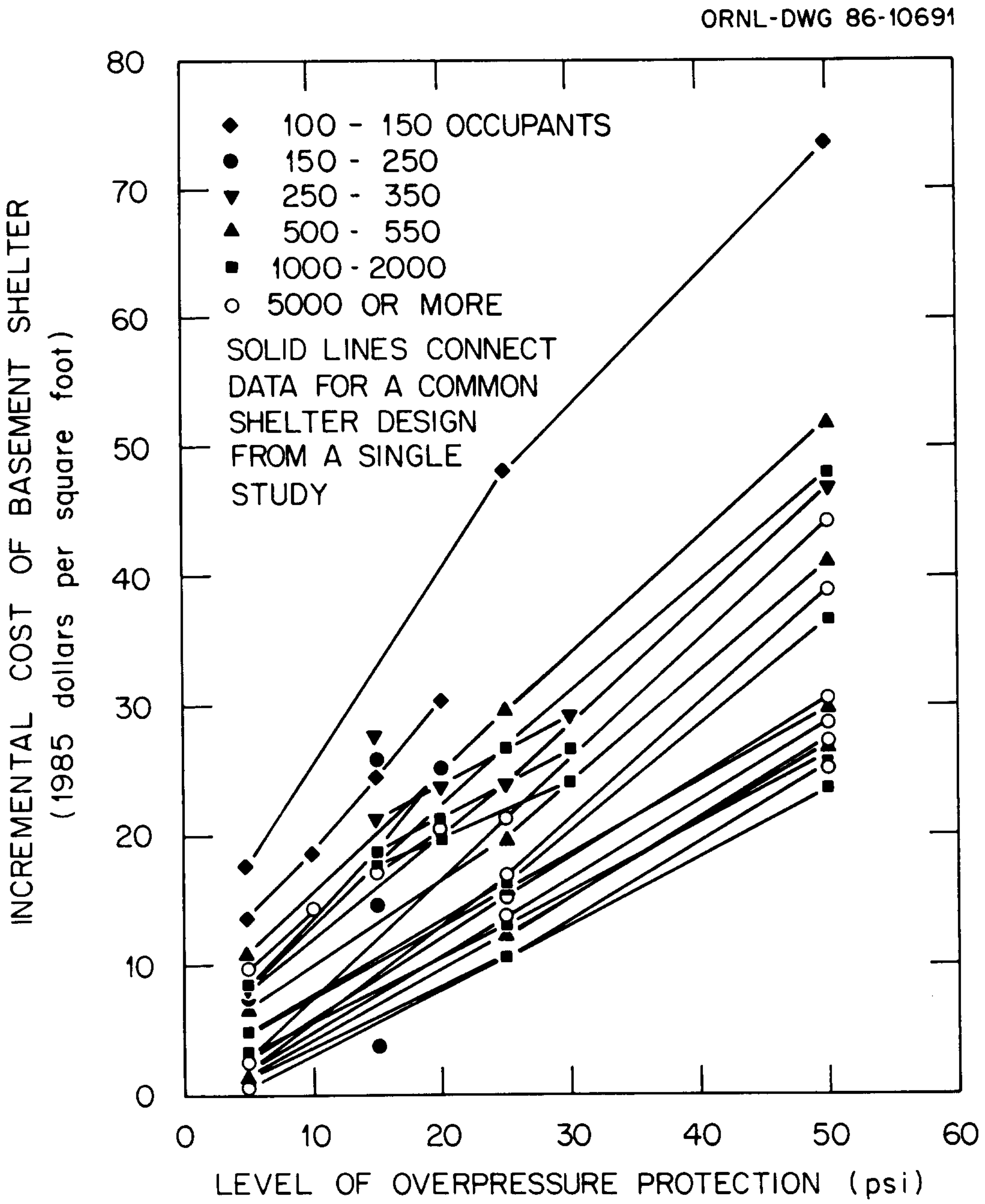


Fig. 7.10. Incremental cost of blast shelter as a function of designed overpressure protection.

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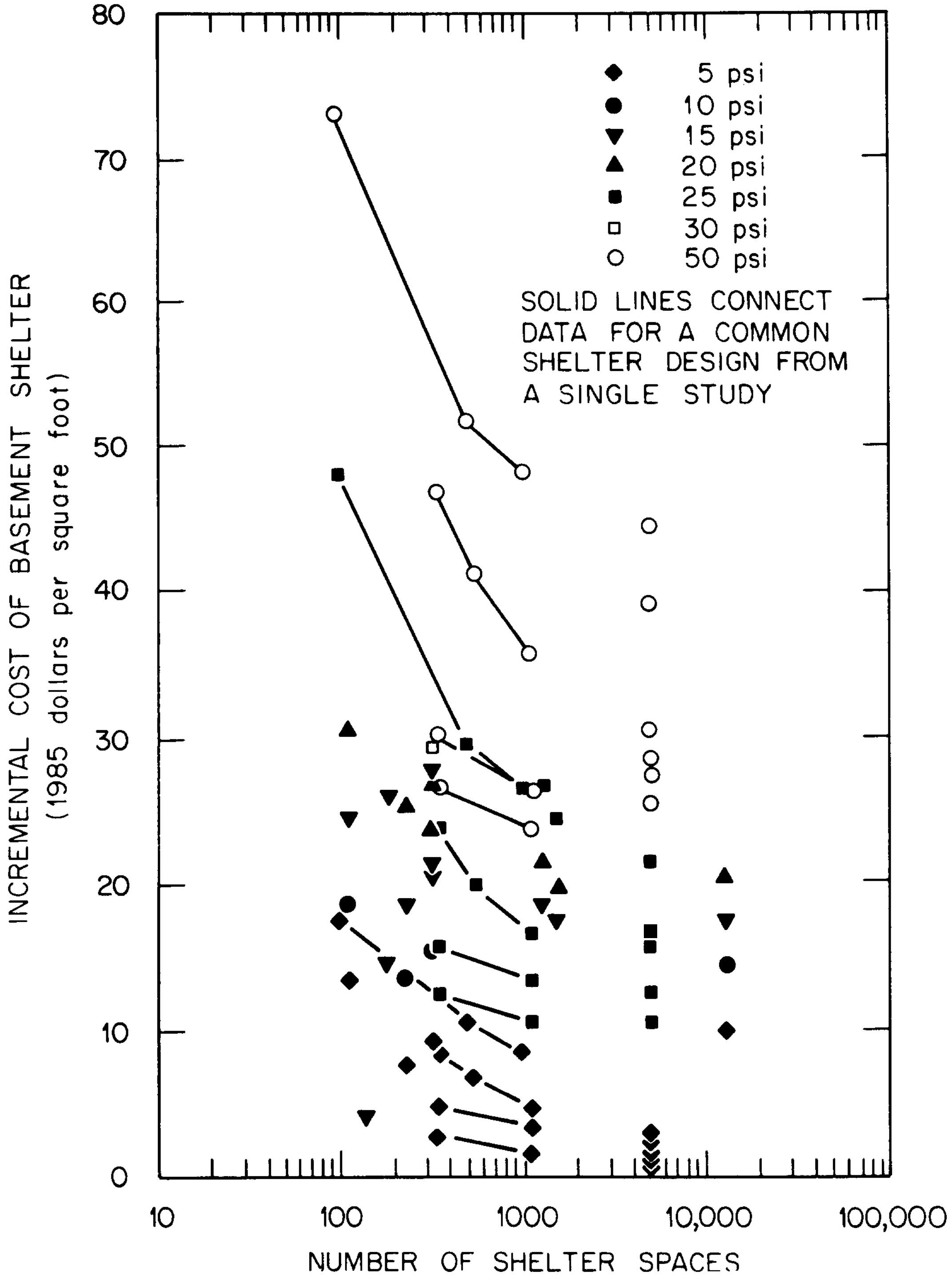


Fig. 7.11. Incremental cost of blast shelter as a function of designed shelter capacity.

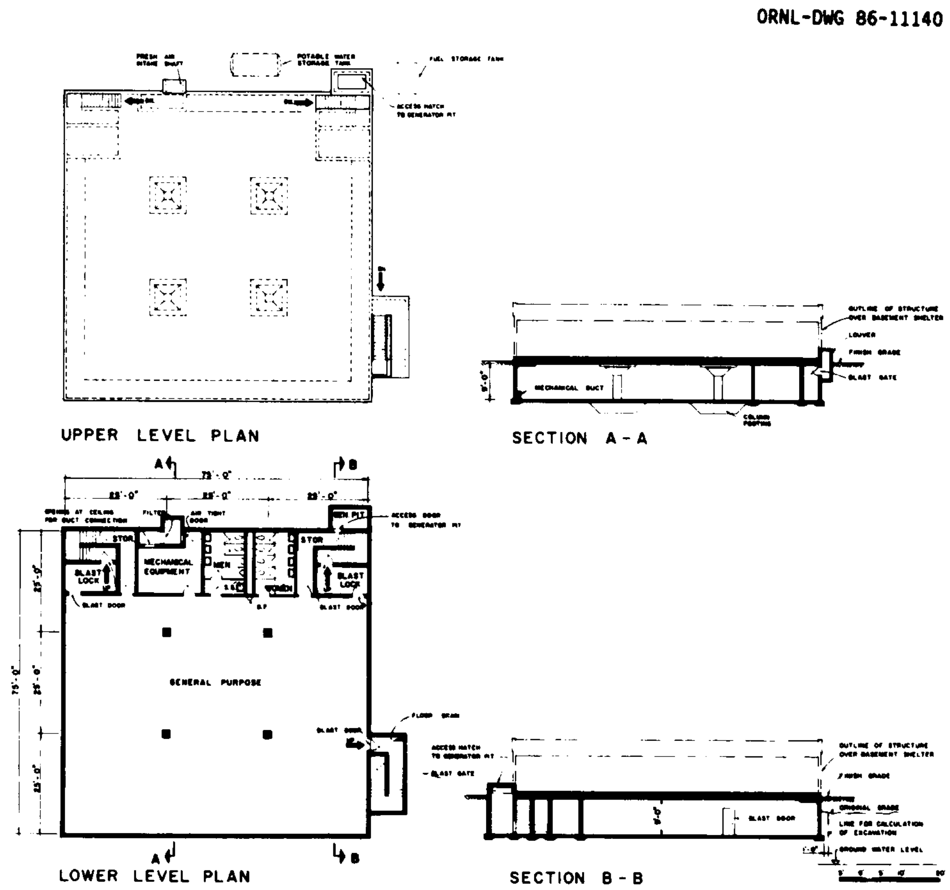


Fig. 7.12. Dual-use basement community center blast shelter.

ORNL-DWG 86-11138

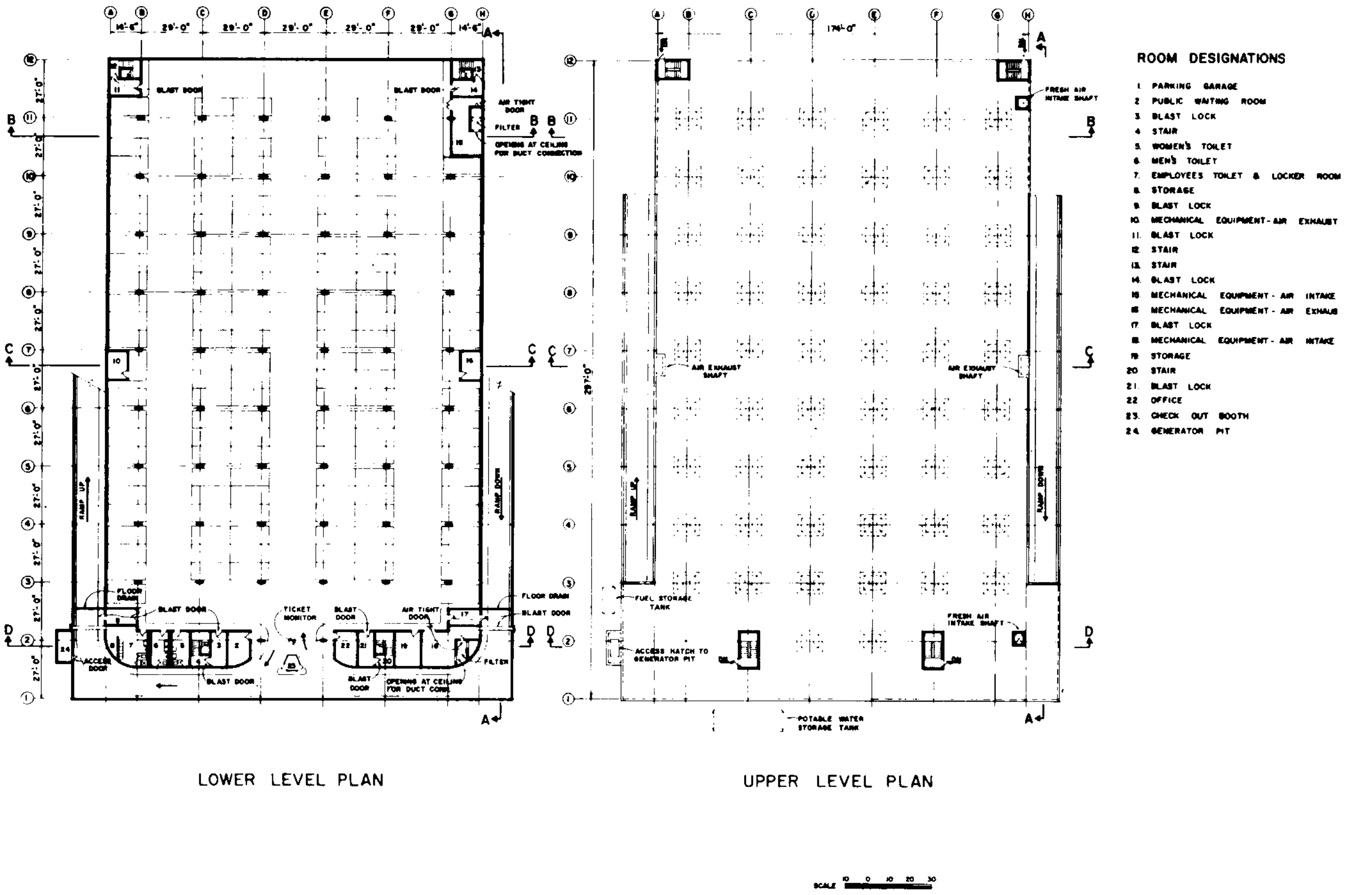


Fig. 7.13a. Dual-use parking garage/blast shelter.

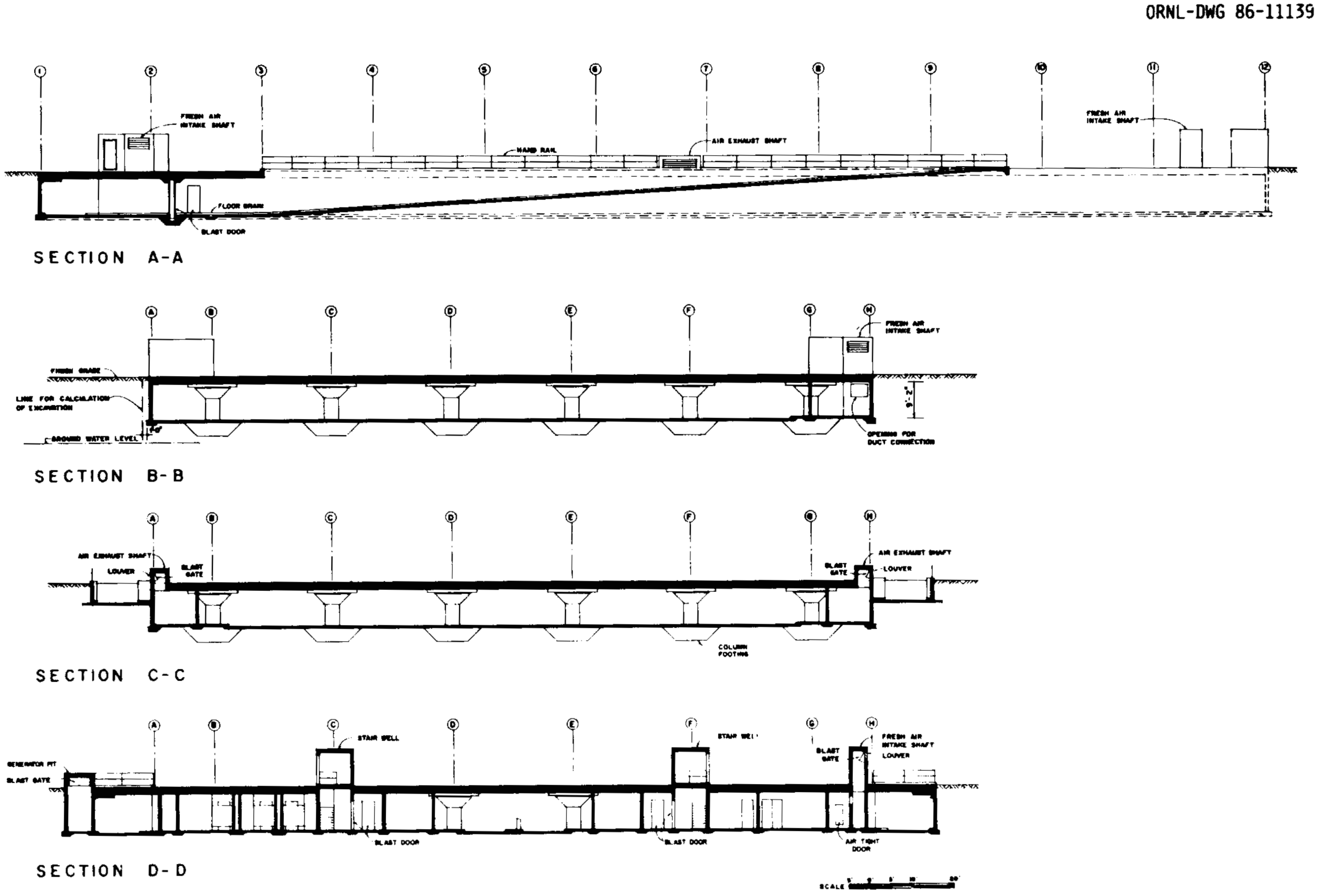


Fig. 7.13b. Dual-use parking garage/blast shelter.

ORNL-DWG 86-11137

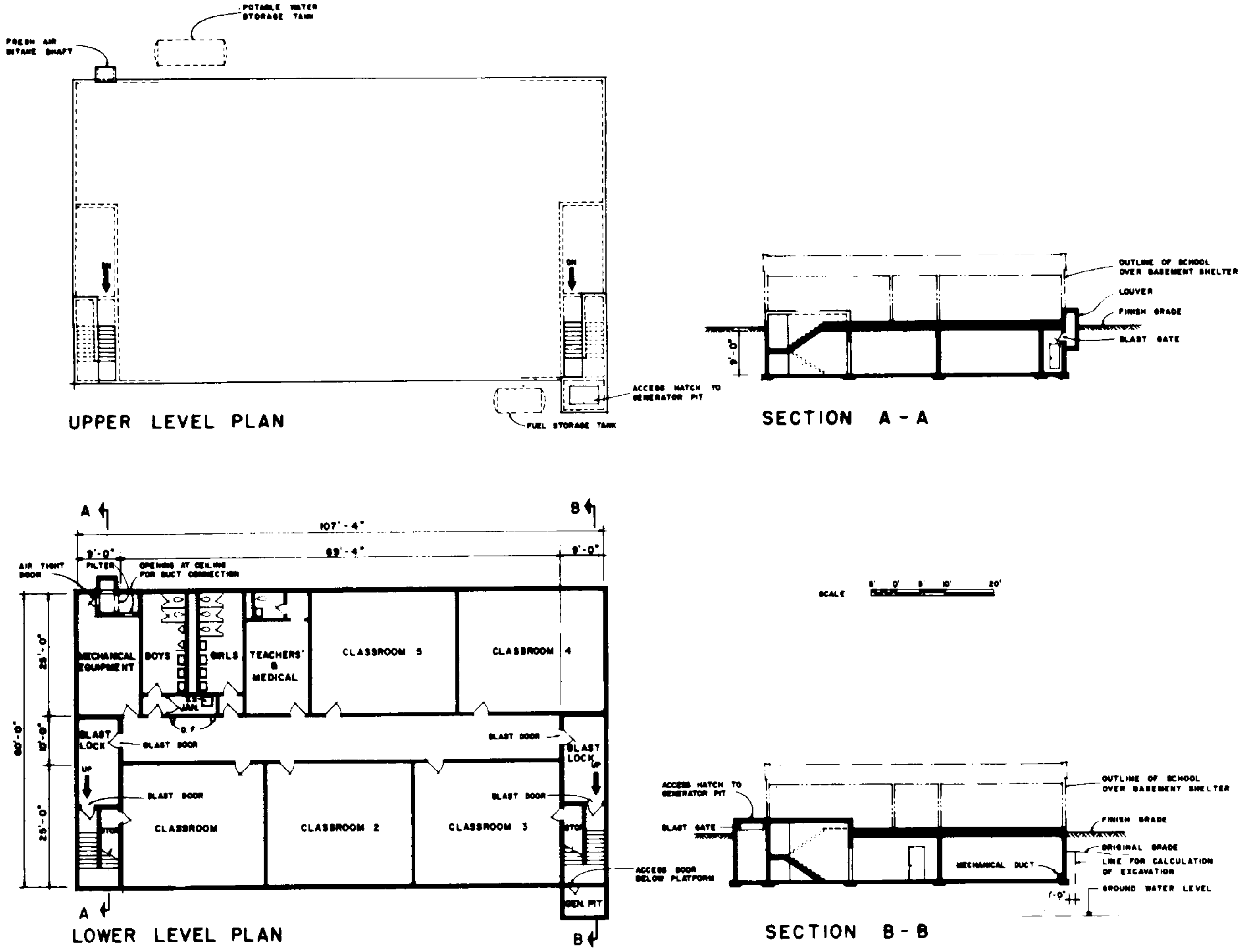


Fig. 7.14. Dual-use basement classrooms/blast shelter.

ORNL-Photo 1613-78

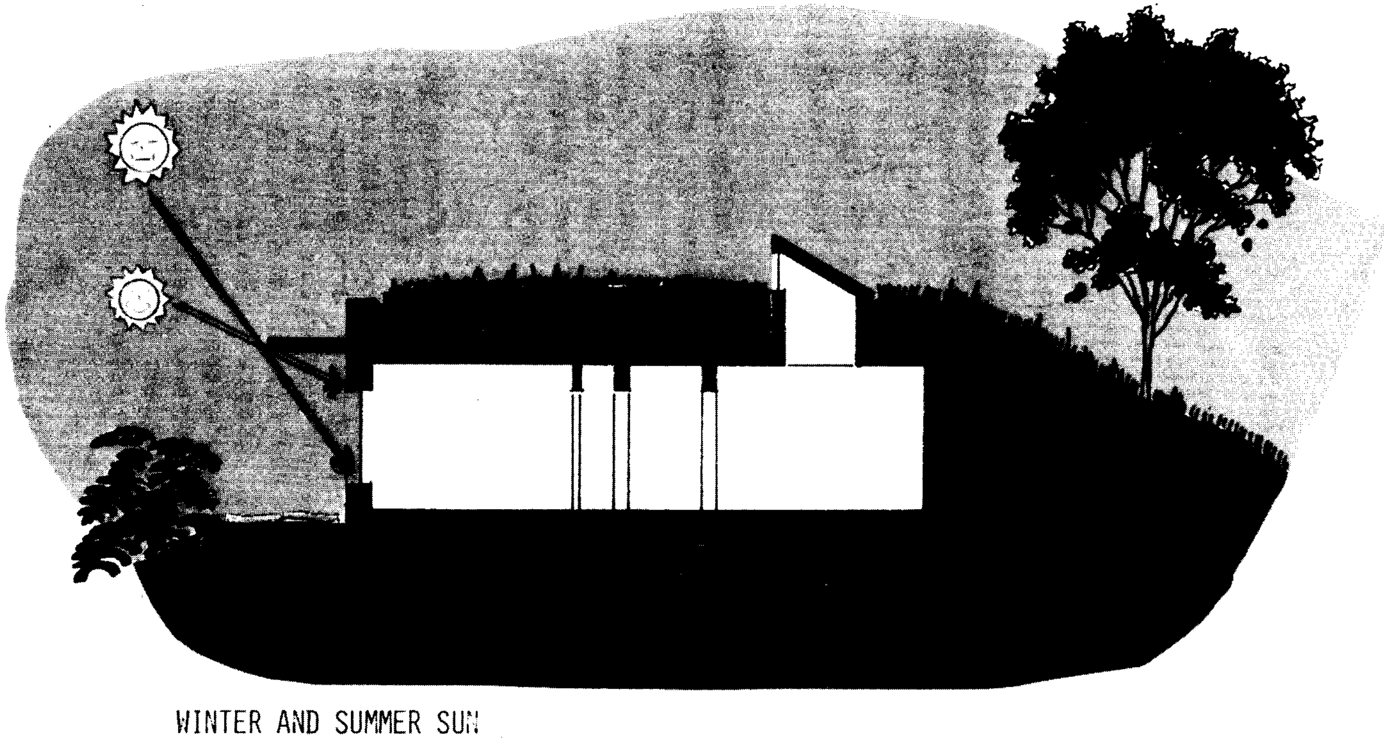
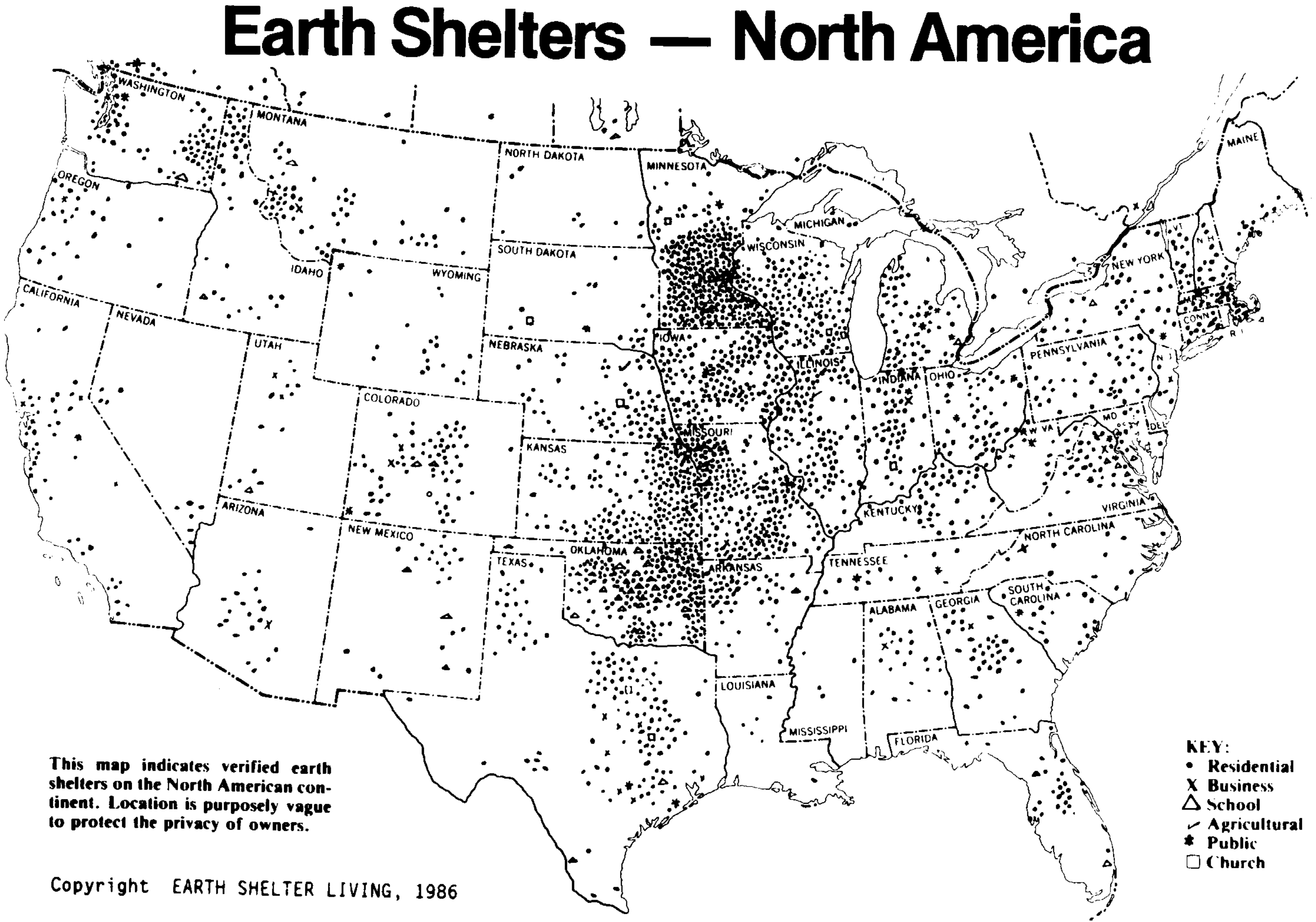


Fig. 7.15. Earth-sheltered housing concept.

ORNL-DWG 84-16268R



This map indicates verified earth shelters on the North American continent. Location is purposely vague to protect the privacy of owners.

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Fig. 7.16. Locations of earth-sheltered buildings in the United States.

(SOURCE: U.S. Army Corps of Engineers, Huntsville Division.) ORNL-DWG 86-14301

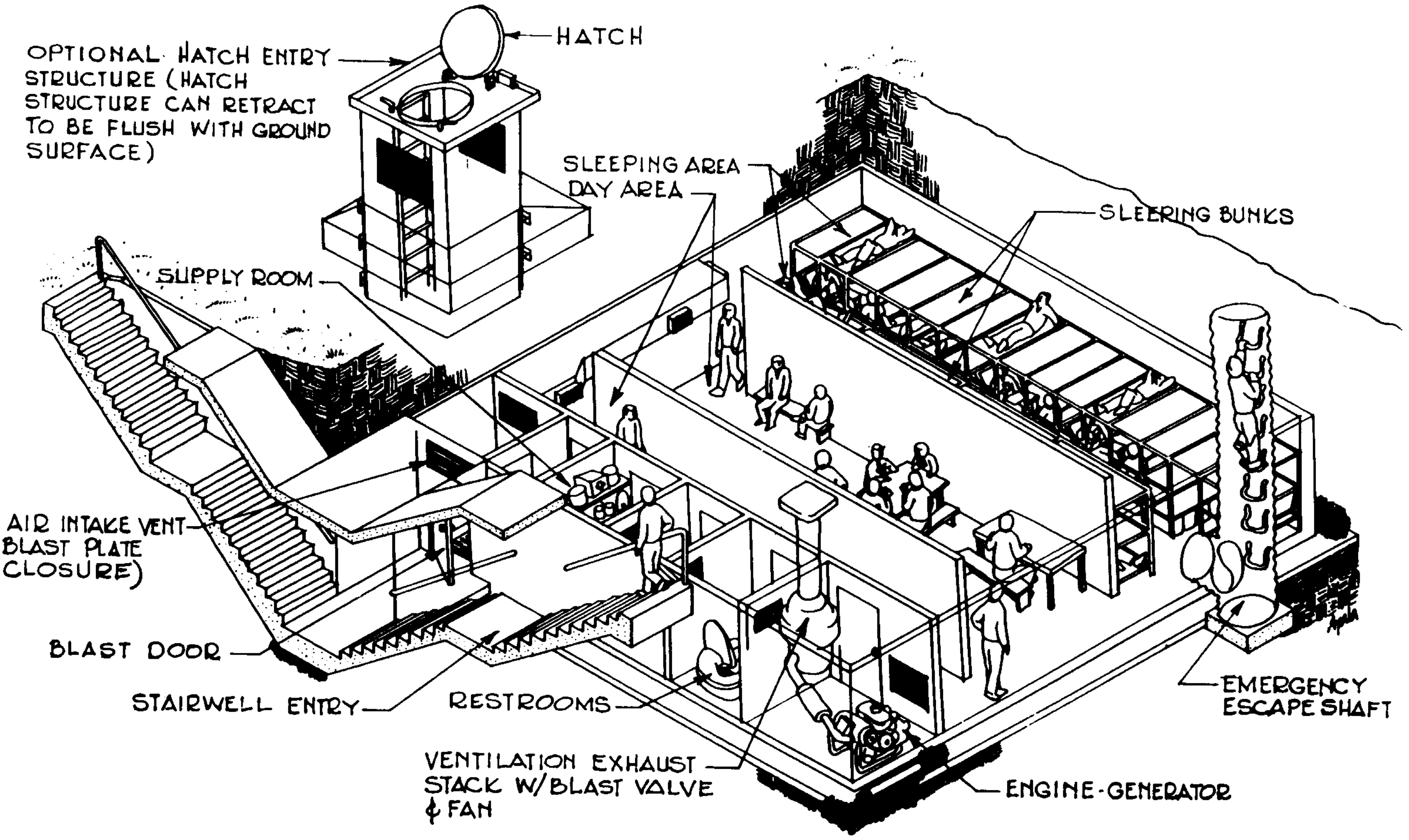

Fig. 7.31. Belowground, reinforced concrete blast shelter for key workers.

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